AFML-TR-65-181
PART II

MECHANISMS ASSOCIATED WITH LONG TIME CREEP PHENOMENA

PART II: EVALUATION OF LONG TIME CREEP RESULTS

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NEW ENGLAND MATERIALS LABORATORY, INC.

TECHNICAL REPORT AFML-TR-65-181, PART II

MARCH 1967

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300 - April 1967 - CO192 - 11-784

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FOREWORD

This report was prepared by New England Materials Laboratory, Inc., Medford, Massachusetts, under USAF Contract No. AF 33(615)-2452. The contract was initiated under Project No. 7351, "Metallic Materials", Task No. 735106, "Behavior of Metals". The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Mr. K. D. Shimmin acting as project engineer.

This report covers work conducted from July 1964 to July 1966.

This technical report has been reviewed and is approved.

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ABSTRACT

A creep-rupture investigation was conducted on two (2) high temperature alloys: a nickel-base age hardened alloy, Udimet 500, and a cobalt-base alloy, L-605. Creep-rupture tests were conducted over a range of rupture lives from 1 - 35,000 hours at 1200, 1350, 1500, 1650 and 1800° F. Some long time tests are in progress and lives of approximately 50,000 hours are expected.

The microstructure of all broken specimens was examined with various techniques and an attempt was made to correlate specific structural changes with the mechanical properties.

Several different parameter techniques were examined to determine their utility in correlating and extrapolating creep and rupture data.

The strength and the limitations of parametric extrapolation was extensively discussed with the example of the Manson-Haford parameter for which a computer program was available.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont's)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF FIGURES (cont'd)

LIST OF TABLES

I. INTRODUCTION

The ability to predict long time strength and deformation properties of metals at elevated temperatures has been strived for as long as this kind of engineering requirement has existed. Today the need to design efficient structures for tens of thousands of hours' life utilizing the most advanced alloys creates increased demands on extrapolation methods.

For the present investigation two (2) typical high temperature alloys -- Udimet 500, a nickel-base alloy and L-605, a cobalt-base alloy -- were selected because they are representative of commonly used high temperature alloys. The objective of the study is the appraisal of various techniques for the extrapolation of creep and rupture data to times in excess of 30,000 hours.

For obvious reasons one would like to avoid long time testing. For many years engineers have used graphical methods to predict long time properties: The most widely used technique is the straight line extrapolation on a double logarithmic plot of stress versus time. On the other hand, various time-temperature parameters have been used. Such a relationship between stress, temperature and time for rupture (or a given amount of creep deformation) can be regarded either strictly as a mathematical tool or else from a point of view of its metallurgical interpretation. In the first case, one would simply attempt to arrange data points in such a way that they permit extension of the experimental range. In the second case, one assumes that what occurs in a long time at a low temperature will occur in a shorter time at a higher temperature. However, if this equivalence is used in the derivation of parametric expressions, the physics of the relation must be properly understood.

In the present investigation test data are being collected covering conditions of both short time and long time tests. The problem to be solved here is, therefore, one of interpolation of data points.

In addition, an attempt is made to combine and arrange data points in a metallurgically meaningful way. This is done by the structural analysis of all test specimens.

A further question to be considered is the reliability of test data and in particular long time rupture and creep data. A good picture of the scatter has been obtained for short time tests; however, the experimental evaluation of scatter at long times would be quite an undertaking.

II. RESULTS AND DISCUSSIONS

1. Long Time Creep Tests

Long time creep tests were continued for both Udimet 500 and L-605 at 1200 and 1500° F. The stresses were chosen on the basis of short time rupture data and an attempt was made to arrive at rupture lives between 10,000 and 50,000 hours. So far test times up to 35,000 hours have been reached.

The results are summarized in TABLE I which includes both data on ruptured specimens and tests in progress. In Figures 1 - 10, the stress-rupture and creep properties are graphically represented. Whereas the stress-rupture curves fall rather consistently on straight lines on a log stress-log time plot, the creep data show more scatter. Nevertheless, this simple graphical method can at least give good guide lines as to the expected times for a given amount of deformation. Stress rupture properties of both L-605 and Udimet 500 can be extrapolated graphically with good accuracy using the 1200 and 1500° F stress rupture curves. The reliability of this approach will be discussed in some detail in another section of this report.

Figures 11 - 14 include the creep curves of the long time tests at 1200 and 1500° F. The two materials exhibit very different plastic behaviors: Udimet 500 shows no primary creep and very little secondary creep. The material deforms very slowly at the beginning of the test and the creep rate gradually increases until fracture. This type of time - deformation characteristic is quite typical for this alloy (and most age-hardened nickel-base alloys) under any condition of temperature and stress.

L-605 on the other hand exhibits a substantial amount of primary creep under all conditions. As can be seen in some of the long time curves, secondary creep may be reached only after 15,000 hours. Again, this type of behavior is characteristic for a group of cobalt-base alloys of this type. The different creep behaviors of the two alloys is also illustrated by the plots of log stress versus log time for a given small amount of plastic deformation. Whereas the Udimet 500 points for 0.1%, 0.5% and 1% creep fall rather nicely on straight lines (Figures 3, 4, 5), the same is not true for the L-605 data (see Figures 8, 9, 10). In the latter case, these small amounts of plastic deformation are all taken up by primary creep, which apparently is much more prone to scatter.

2. <u>Structural Observations During Long Time Creep Exposure</u>

The structure of all broken specimens was examined on longitudinal sections with both electron and light microscopy. Pictures were taken at magnifications of 1000X and 15000X. The conditions for the preparation of the sample surfaces are given in Table II. Emphasis was placed on observations indicating a change in micro-constituents, appearance of grain boundaries and crack initiation. It is thought that extrapolation methods of any kind can only be applied rigorously if the structures, as well as deformation and fracture mechanisms, are the same within the range of extrapolation.

a. Udimet 500

The microstructural constituents of this alloy consist merely of a fine dispersion of the γ' precipitate in the nickel-base matrix. Some chromium carbide is present in the grain boudaries. During creep exposure at 1200° F, hardly any changes take place: The γ' particles have the same size over the whole range of test time (up to 18,000 hours). No agglomeration of the chromium carbide particles can be noted. Cracking occurs along the grain boundaries. (See Figures 15 - 28.)

At 1500° F growth of both the γ' and the grain boundary carbides can be noticed. The observations are summarized in TABLE III. This growth starts with test times in excess of a few hundred hours and is very marked after a few thousand hours.

All cracking occurs along grain-boundaries. (See Figures 29 - 43)

b. L-605

In the as received condition L-605 is a single phase alloy (See Figure 44) but precipitation starts in the grains and on grain boundaries with very short test times and at a temperature as low as 1200° F (Figures 45 - 58). The grain precipitate can be found mostly in twin planes and along specific crystallographic planes.

At 1500° F, precipitation of second phase particles starts with very short test times in both grains and grain-boundaries. With test durations over 100 hours, the second phase particles agglomerate rapidly. An analysis of the electrolytically separated residue shows that both Co_2W and carbides of the M_6C type are present. (See Figures 59 - 70).

Under all conditions, cracking occurred along grain-boundaries.

(Further comments on structural observations will be found in the following paragraph.)

3. Extrapolation of Stress Rupture and Creep Data by Parameter Techniques

a. General Considerations

With the exception of graphical methods, all extrapolation techniques attempt to define, in mathematical terms, a general description of the variation of creep strength (rupture or specific amount of plastic deformation) with stress and temperature. This is then specialized for a particular material by using relatively short time data to generate values for the constants and parameters, and the specialized equation is then used to predict the long time properties of the material. This concept is based on the assumption that all creep-rupture or creep-deformation data for a given material can be correlated to produce a single "master-curve" wherein the stress (or log stress) is plotted against a parameter involving a combination of time and temperature. Extrapolation to long times can then be obtained from this curve, which can presumably be constructed by using only short-time data. It is of great importance to know how many tests have to be run and the minimum test times required to obtain a reliable master curve.

The most widely used extrapolation techniques utilize a time-temperature parameter based on a rate equation of the type

$$\text{rate} = Ao \exp \ (-B/T)$$

In terms of creep rupture properties this becomes:

$$t_r = A_1 \exp \ (B_1/T)$$

where T is the absolute temperature, t_r the rupture time and A_1 and B_1 are constants for a given stress. In different techniques various assumptions are made regarding the variation of these constants with stress.

If we put the last equation in logarithmic form, we arrive at the Larson-Miller parameter (Ref. 2).

$$P_t = f(\sigma) = T(\log t_r + K_1)$$

where P_t is the parameter and K_1 a constant.

If on the other hand we suppose that B_1 is a constant and A_1 varies with stress, we have

$$\theta = f(\sigma) = t_r \exp(B_1/T)$$

which is in essence the Dorn parameter (Ref. 3).

The Manson-Haford parameter (Ref. 4) departs somewhat from the other parameters in that the iso-stress lines in a plot of log t_r versus T are assumed to be linear and to intersect at log t_a and T_a. One arrives then at the following form:

$$P = f(\sigma) = \frac{T - T_a}{\log t_r - \log t_a}$$

If on the other hand the iso-stress lines appear to be parallel, the parameter is of the form:

$$\psi = \log t_r - S\,T \qquad (S = \text{constant})$$

A further advance in the practical application of parametric methods was the development of an objective least-squares method for the determination of optimum values of the constants and thus avoiding the use of the judgment on the part of the analyst.

b. Parametric Presentation of Creep and Rupture Data

All available data for rupture life and time for 1, 0.5 and 0.1% creep were evaluated and plotted with the various parametric techniques. (For a complete listing of all the short time test results see Reference 1.) The test temperatures included 1200, 1350, 1500, 1650 and 1800° F. A computer program was available for only the Manson-Haford parameter for an objective evaluation of the data points.* For this reason and also because the same important conclusions can be made on the basis of several of the parametric plots, only the Manson-Haford plots were used for the following discussion.

With the aid of the computer program (Fortran IV) creep deformation and stress-rupture results were processed in the following way:

(1) Data for time to rupture as well as time to 0.1, 0.5 and 1% creep were used throughout the evaluation.

(2) Several arbitrary cut-off points in test time were chosen, namely, 200, 1000 and 10,000 hours. Test results were then processed with the assumption that only results up to the particular test time were available. In addition, sets of data with all available test results (including all long time tests) were processed.

(3) The constants for the linear Manson-Haford parameter were then determined with the aid of the computer program. For the determination of the optimum values the least-squares method was used.

(4) For those cases for which the value of Ta in the linear Manson-Haford parameter as less than -3000, a modified parameter ψ was used ($\psi = \log t - ST$). The choice of this parameter would indicate that iso-stress lines are parallel on a temperature versus log time plot.

* The authors are indebted to the Lewis Research Center for the processing of the data; our thanks go in particular to Messrs. S. S. Manson, A. Mendelson and E. Roberts.

(5) In all the plots data points for long time tests were put in. These added test results had not been used for the original determination of the constants of a particular plot, but the value of the parameter of those results was determined using those same constants. The deviation of the long time data points from the general course of the master curve gives an indication of the reliability of the extrapolation.

(6) The plots which include all data points give an indication of the reliability of interpolation within the complete test time span.

A summary of the parameters and the constants is given in TABLES IV and V for all the groups of data processed. It shows that the standard linear parameter was used for all the creep results except for 0.1% plastic strain in L-605 where the "parallel lines" parameter ψ = log t - ST was more suitable. Also, all rupture results were presented on the basis of the second of the two parameters.

A discussion of the individual plots (Figures 71 - 98) is most conveniently done in treating the two materials separately.

Udimet 500 (See Figures 71 - 85)

The major conclusions that can be drawn on the basis of the rupture plots are the following:

(1) Within the temperature range of 1200 - 1650° F extrapolation with the aid of a temperature/time parameter is as accurate as the reproducibility of tests under identical conditions of temperature and stress.

(2) Extrapolation on the basis of 200 hours test time is definitely less reliable than extrapolation with data points up to 1000 or 10,000 hours. (The same can be found on the basis of the change of constant S.)

(3) 1800° F data should definitely not be used for extrapolation purposes as the reproducibility is very poor at this temperature. At all lower temperatures Udimet 500 has a rather stable structure with a fine dispersion of the γ' precipitate, whereas at higher temperatures agglomeration can occur in an unpredictable manner which causes variable crack progress and, therefore, wide scatter in rupture data. (See also Figures 15 - 43)

The 1% and 0.5% creep data fall all on rather smooth curves which would indicate that creep (other than fracture) is less structure sensitive with this type of an alloy. The plots indicate that extrapolation to long time data points is possible even with only short time data (200 hours) on hand. It should be noted, however, that the stress versus parameter curves based on 200 hours data are rather steep, which means that a small change in stress does not result in much of a change in the value of the parameter. This, of course, weakens the value of the extrapolation. In all cases the long time data points fall well within the general scatter band of the rest of the data points.

The picture looks somewhat different with the 0.1% creep data: the general scatter of all results is considerably increased, but amazingly, the reliability of extrapolation does not seem to increase with longer time test data: the constants log t_A and T_A do not change with the different sets of data points.

<u>L-605</u> (See Figures 86 - 98)

The following observations can be made on the basis of the <u>rupture data</u> points:

(1) The basis for the extrapolation does not change much with increasing test time.

(2) The reproducibility of results is generally better with higher temperature.

(3) A kink in the master curve around a value of ψ = 16 confirms the age-hardening effect of the precipitate observed in the micro-structure. This precipitation was observed with long time tests at low temperatures and shorter times at intermediate temperatures. Within that range of test conditions the accuracy of a rupture life prediction is very poor, as can be seen in Figures 86 - 89.

Extrapolation of 1% plastic strain at high temperatures can be quite reliable, provided the master curve is determined on the basis of tests up to 1000 hours. Below 1500° F, but particularly at 1350 and 1200° F, the scatter is considerable due to the same structural instability mentioned in the discussion of the rupture data. It is, therefore, very difficult to extrapolate long time data for this low temperature range.

Extrapolation of lower plastic strain data becomes quite hazardous with this alloy. Whereas 0.5% creep values can be predicted within the high temperature range on the basis of 1000 hour tests, not much can be done with 0.1% data. In looking at the results it should be kept in mind that none of the plots shows any real long time data for these small amounts of creep. The long time creep curves show clearly that a specimen with a life expectancy of over 50,000 hours may very well deform plastically by a considerable amount during its early life time. It is, therefore, very difficult to establish a basis for the extrapolation of long time data for very small amounts of creep if the deformation pattern of the alloy includes a considerable amount of primary creep.

III. SUMMARY AND CONCLUSIONS

The present evaluation of extrapolation techniques applied to creep and rupture data of two (2) superalloys leads to a number of impo tant observations:

(1) Extrapolation with the aid of a time/temperature parameter can be as accurate and reliable as other methods (such as graphical extrapolation), provided one knows the behavior of the material in question and, therefore, is well aware of specific restrictions in the range of applicability of the parametric techniques. This would preclude that fairly long time tests have to be conducted over the whole temperature range for a given type of a material if extrapolation to long time data is desired.

(2) A more severe restriction to the accuracy of extrapolation is caused by a lack of reproducibility of data points even within one lot of a given material. The scatter in test data varies with alloys and conditions, particularly test temperature. It turns out that the uncertainty in extrapolation caused by a lack of reproducibility of a data point can be as severe as the uncertainty caused by a change in test temperature.

(3) The results show that increased accuracy in extrapolation can be obtained by basing the determination of a parameter master curve on longer time tests. In most instances 1000 hours appear to be a reasonable cut-off time. With longer time tests the additional gains are not significant. (Again, the remark made under (1) should be kept in mind: the general behavior of the material should be known.)

(4) In many instances observed in the present investigation creep data (such as 0.1, 0.5 and 1% plastic strain) can be extrapolated as accurately as rupture data. An exception should be made for low strain data (0.5% or lower) of alloys exhibiting large amounts of primary creep.

(5) The observations made during the present investigation suggest the following procedure for a most successful approach to the extrapolation of rupture and creep data of a specific material:

(a) The creep behavior of the material should be known in general over the complete range of temperatures of interest, including all temperatures to be included in short time tests.

(b) A large number of data points should be collected with test time up to about 1000 hours.

(c) A master curve can be obtained using the least-squares method for the determination of optimum values of the constants.

(d) The actual determination of a point on the master curve should be done on the basis of a statistical analysis of the data at many different stress levels.

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(1) Widmer, R., Dhosi, J. M., Mullendore, A., Grant, N. J.: Mechanisms Associated with Long Time Creep Phenomena. Part I: Presentation of Creep Data and Structural Analysis. Technical Report AFML-TR-65-181.

(2) Larson, F. R., Miller, J.: A Time-Temperature Relationship for Rupture and Creep Stress. Trans. ASME, Vol. 74, No. 5, July 1952, p.p. 765-771.

(3) Manson, S. S., Haford, A. M.: A Linear Time-Temperature Relation for Extrapolation of Creep and Stress-Rupture Data. NACA TN 2890, 1953.

(4) Orr, R. L., Sherby, O. D., Dorn, J. E.: Correlations of Rupture Data for Metals at Elevated Temperatures. Trans. ASM, Vol. 46, 1954, p.p. 113-128.

TABLE I: Summary of Long Time Creep Tests Results

Stress psi	Test Time Hours	Hours to 0.5% Plastic Strain 1.0%	0.5%	0.1%	Total Elongation* %	Reduction In Area %	Minimum Creep Rate In/In/Hour	Expected Rupture Life Hours
				U-500 - 1200° F				
74,000	17,840	9,800	6,000	1,900	7.0	8.8	$8.5x10^{-7}$	Ruptured
71,500	24,598	10,900	7,400	3,000	6.321	-	$2.6x10^{-7}$	30,000
70,000	22,993	18,500	13,800	5,700	2.258	-	$2.1x10^{-7}$	50,000
				U-500 - 1500° F				
19,000	14,773	6,400	4,400	1,100	12.9	20.4	$9.1x10^{-7}$	Ruptured
18,000	12,880	4,300	2,600	600	13.0	12.6	$1.5x10^{-6}$	Ruptured
16,500	24,733	15,200	10,400	2,000	6.7	15.3	$3.7x10^{-7}$	Ruptured
15,000	16,724	-	-	4,000	0.480	-	$2.3x10^{-7}$	50,000
13,500	16,757	-	-	4,200	0.303	-	$1.4x10^{-7}$	50,000+
				L-605 - 1200° F				
29,500	21,720	2,350	650	0.1	3.1	3.8	$5.2x10^{-7}$	Ruptured
28,000	10,192	5,000	1,750	300	1.4	1.6	$4.5x10^{-7}$	Ruptured
26,500	35,304	10,000	2,000	550	1.440	-	$1.7x10^{-7}$	40,000
25,000	22,868	16,500	2,400	760	1.112	-	$3.5x10^{-7}$	50,000
24,000	22,915	18,500	2,600	820	1.089	-	$2.9x10^{-7}$	50,000+
				L-605 - 1500° F				
13,000	11,075	225	56	7	9.6	6.2	$4.0x10^{-6}$	Ruptured
11,500	13,018	425	119	10	4.9	1.5	$8.5x10^{-7}$	Ruptured
10,500	34,600	450	110	1	7.3	5.6	$4.8x10^{-7}$	Ruptured
10,000	19,936	1,700	340	18	1.582	-	$3.0x10^{-7}$	50,000
9,500	35,375	1,200	300	1	2.090	-	$1.8x10^{-7}$	50,000+

* or total plastic strain respectively.

TABLE II: Preparation of Metallographic Specimens

Material	Etchant for light microscopy	Etchant for electron microscopy
Udimet 500	Modified aqua regia	Hydrochloric acid with 4% HNO_3 and 2% H_2SO_4
L-605	Vilella's Reagent modified with $KMnO_4$ electrolytically	Same as above

Replica technique was used for electron micrographs: replicas were shadowed with germanium.

TABLE III: Structural Changes in Udimet 500 During Long Time Creep Exposure

A. Test Temperature 1200° F: With rupture lives up to 17,800 hours no appreciable changes in the size of the γ' precipitate (diameter of particles .1 - .3 micron) or the thickness of grain boundary areas affected by grain-boundary sliding.

B. Test Temperature 1500° F:

Stress, psi	Rupture life hours	Approximate average diameter of γ' particles, microns	Approximate average width of grain boundary area, microns
as received	-	.1 - .3	.3
80,000	1.7	.1 - .3	.5 - 1
72,000	5.0	.2 - .4	.5 - 1
60,000	10.5	.2 - .4	.5 - 1
55,000	33	.2 - .4	.5 - 1
45,000	159.6	.2 - .4	.5 - 2
42,500	193.0	.2 - .4	.5 - 2
39,000	421.2	.2 - .4	.5 - 2
35,000	441.6	.2 - .6	.5 - 2
32,500	548.8	.2 - .6	.5 - 2
30,000	1,255.4	.2 - .6	.5 - 2
26,000	2,401.1	.2 - .6	.5 - 2
23,000	7 146.6	.2 - 1	.5 - 2
19,000	14,773	.2 - 1	1 - 2
18,000	12,880	.2 - 1	1 - 2
16,500	24,733	.2 - 1	1 - 2

TABLE IV: Udimet 500; Constants for Manson-Haford Parameter

	Parameter	S	T_A	$\log T_A$
Rupture Data				
All data	$\psi = \log t - ST$	-0.01226	-	-
Data up to 10,000 hrs.	"	-0.01231	-	-
Data up to 1,000 hrs.	"	-0.01153	-	-
Data up to 200 hrs.	"	-0.01070	-	-
1% Plastic Strain				
All data	$P = \frac{T - T_A}{\log t - \log T_A}$	-	200	19.099
Data up to 10,000 hrs.	"	-	200	19.119
Data up to 1,000 hrs.	"	-	200	19.303
Data up to 200 hrs.	"	-	1000	35.054
0.5% Plastic Strain				
All data	$P = \frac{T - T_A}{\log t - \log T_A}$	-	400	16.528
Data up to 10,000 hrs.	"	-	400	16.438
Data up to 1,000 hrs.	"	-	400	16.966
Data up to 200 hrs.	"	-	0	21.529
0.1% Plastic Strain				
All data	$P = \frac{T - T_A}{\log t - \log T_A}$	-	400	12.260
Data up to 10,000 hrs.	"	-	-	-
Data up to 1,000 hrs.	"	-	700	12.274
Data up to 200 hrs.	"	-	700	12.341

TABLE V: L-605: Constants for Manson-Haford Parameter

	Parameter	S	T_A	log T_A
Rupture Data				
All data	$\psi = \log t - ST$	-0.01058	-	-
Data up to 10,000 hrs.	"	-0.01068	-	-
Data up to 1,000 hrs.	"	-0.01007	-	-
Data up to 200 hrs.	"	-0.009774	-	-
1% Plastic Strain				
All data	$P = \frac{T - T_A}{\log t - \log T_A}$	-	200	14.938
Data up to 10,000 hrs.	"	-	200	14.727
Data up to 1,000 hrs.	"	-	200	14.677
Data up to 200 hrs.	"	-	700	9.582
0.5% Plastic Strain				
All data	$P = \frac{T - T_A}{\log t - \log T_A}$	-	200	11.331
Data up to 10,000 hrs.	"	-	-	-
Data up to 1,000 hrs.	"	-	700	8.725
Data up to 200 hrs.	"	-	1000	6.054
0.1% Plastic Strain				
All data	$\psi = \log t - ST$	-0.006835	-	-
Data up to 10,000 hrs.	"	-	-	-
Data up to 1,000 hrs.	"	-	-	-
Data up to 200 hrs.	"	-0.005809	-	-

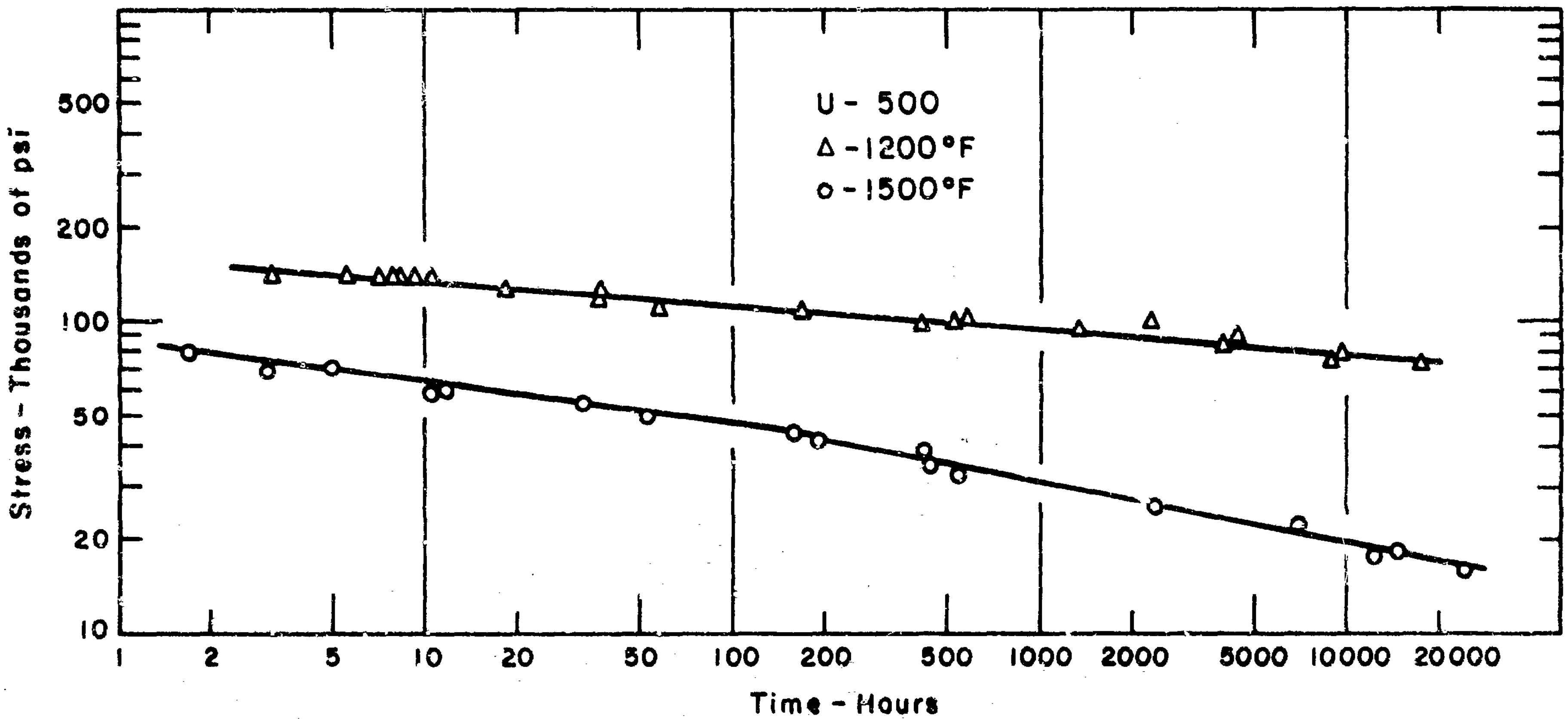


Figure 1. Log stress versus log time to rupture for Udimet 500.

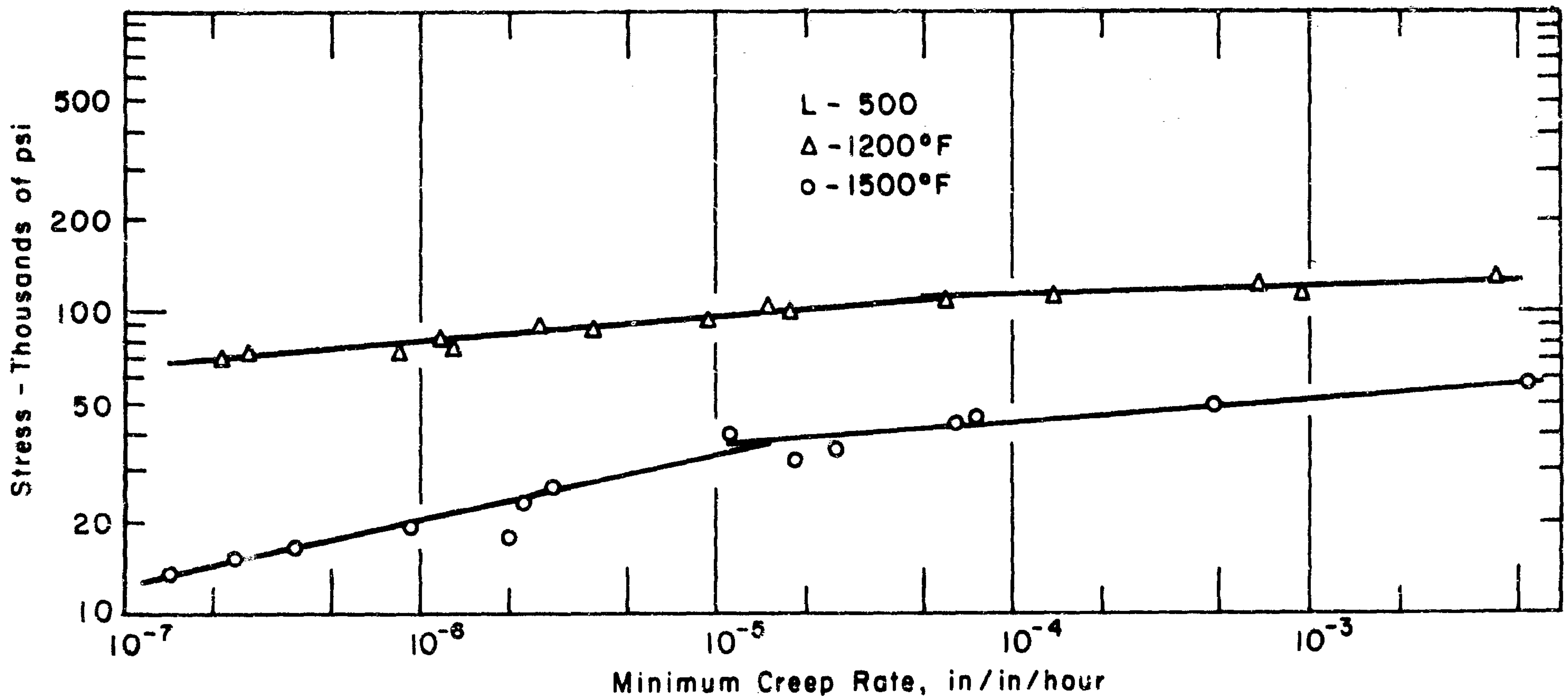


Figure 2. Log stress versus log minimum creep rate for Udimet 500.

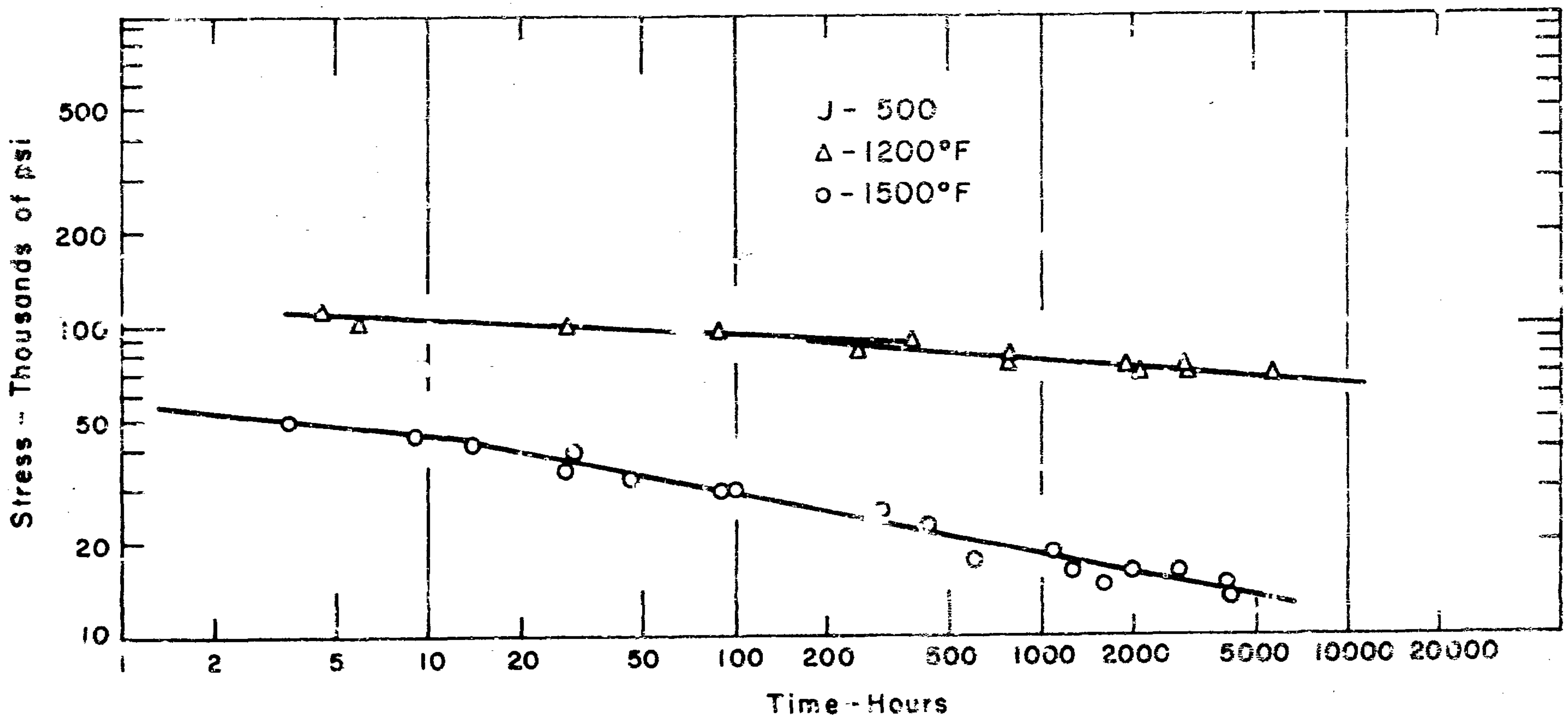


Figure 3. Log stress versus log time to 0.1% plastic strain for Udimet 500.

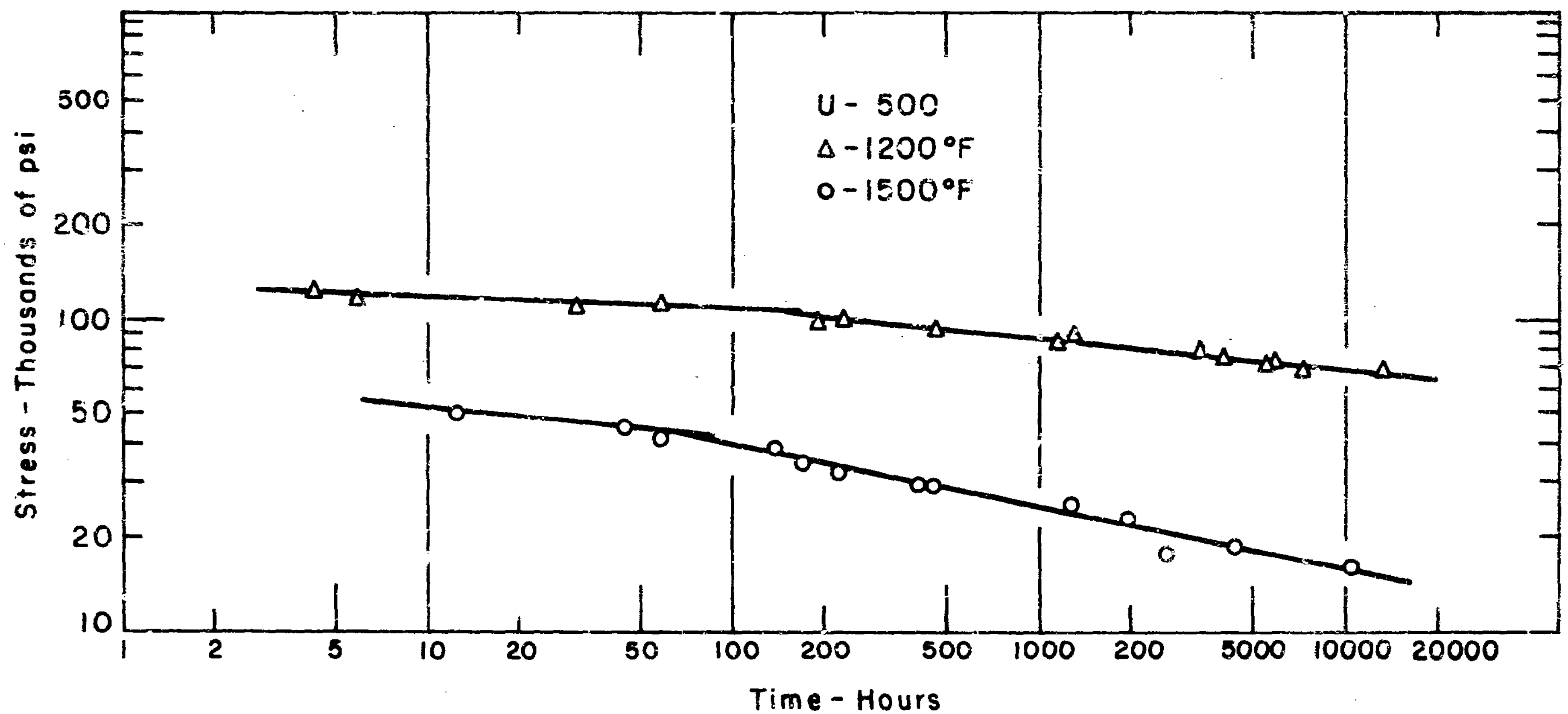


Figure 4. Log stress versus log time to 0.5% plastic strain for Udimet 500.

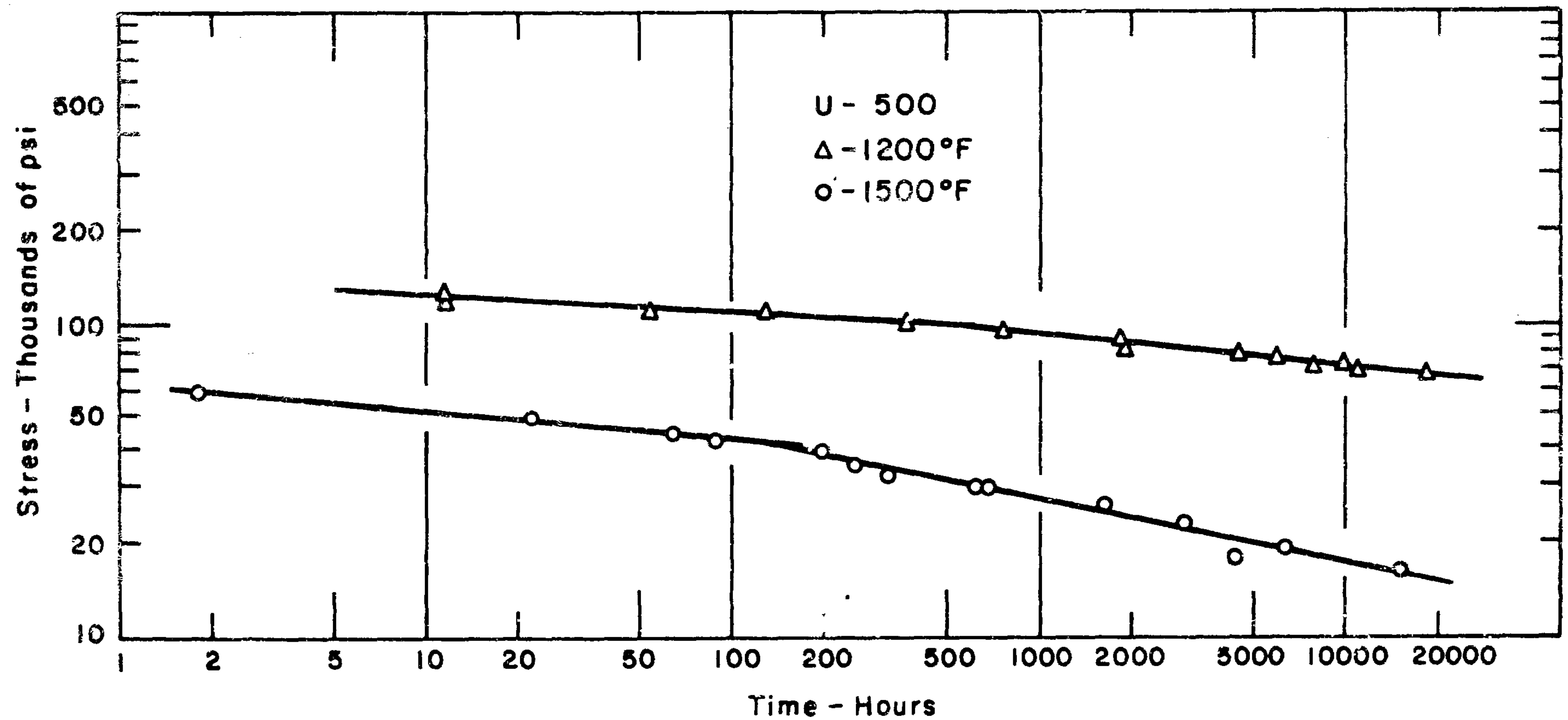


Figure 5. Log stress versus log time for 1.0% plastic strain for Udimet 500.

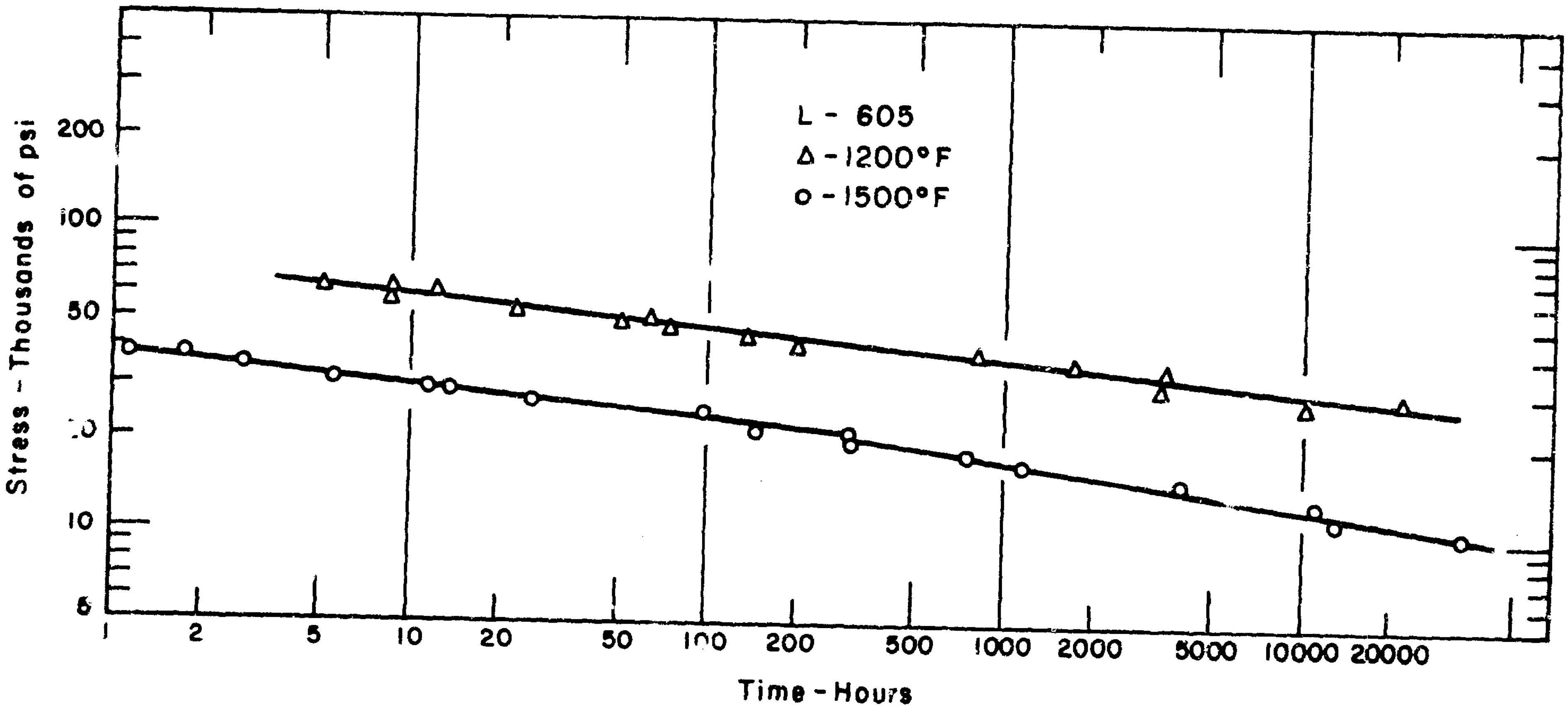


Figure 6. Log stress versus log time to rupture for L-605.

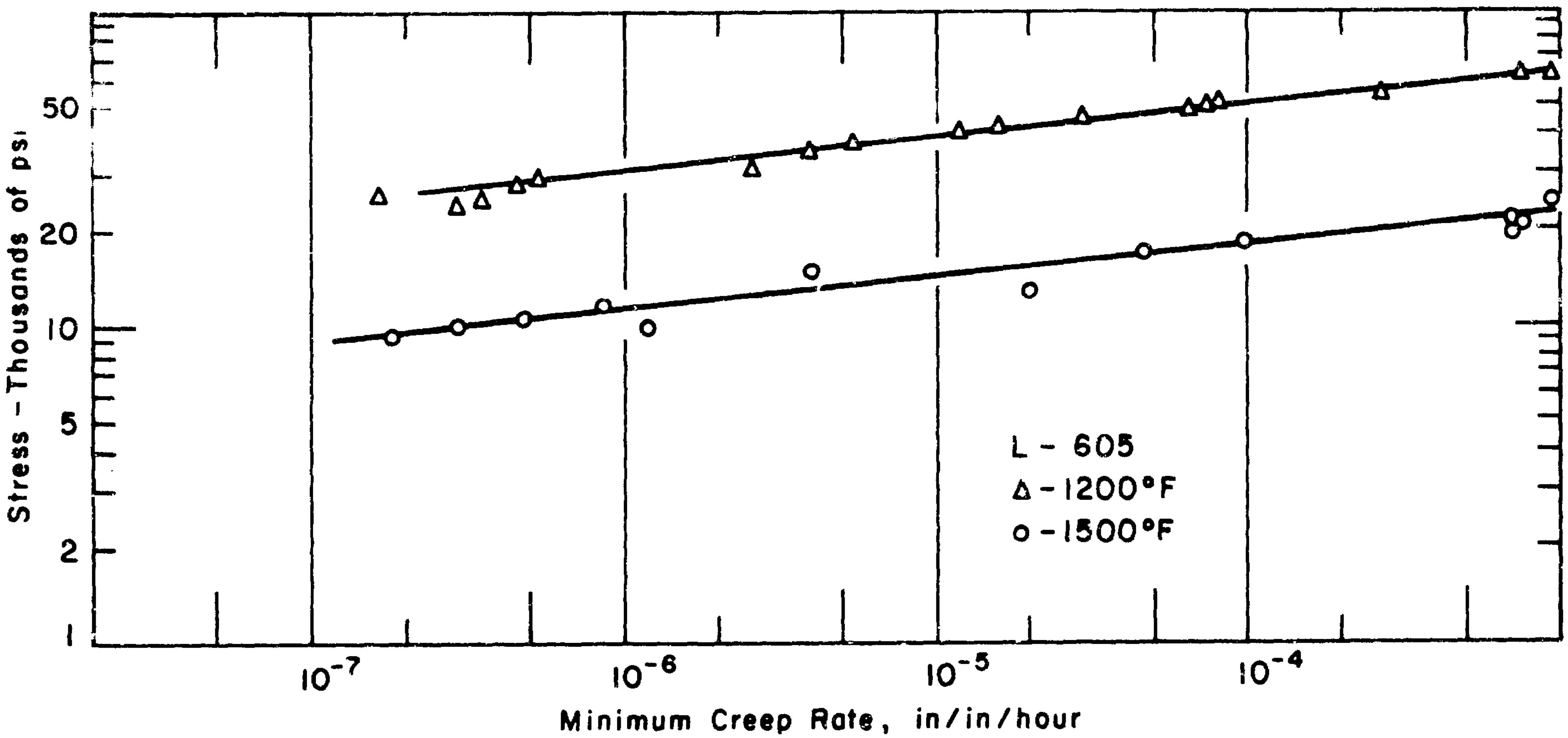


Figure 7. Log stress versus log minimum creep rate for L-605.

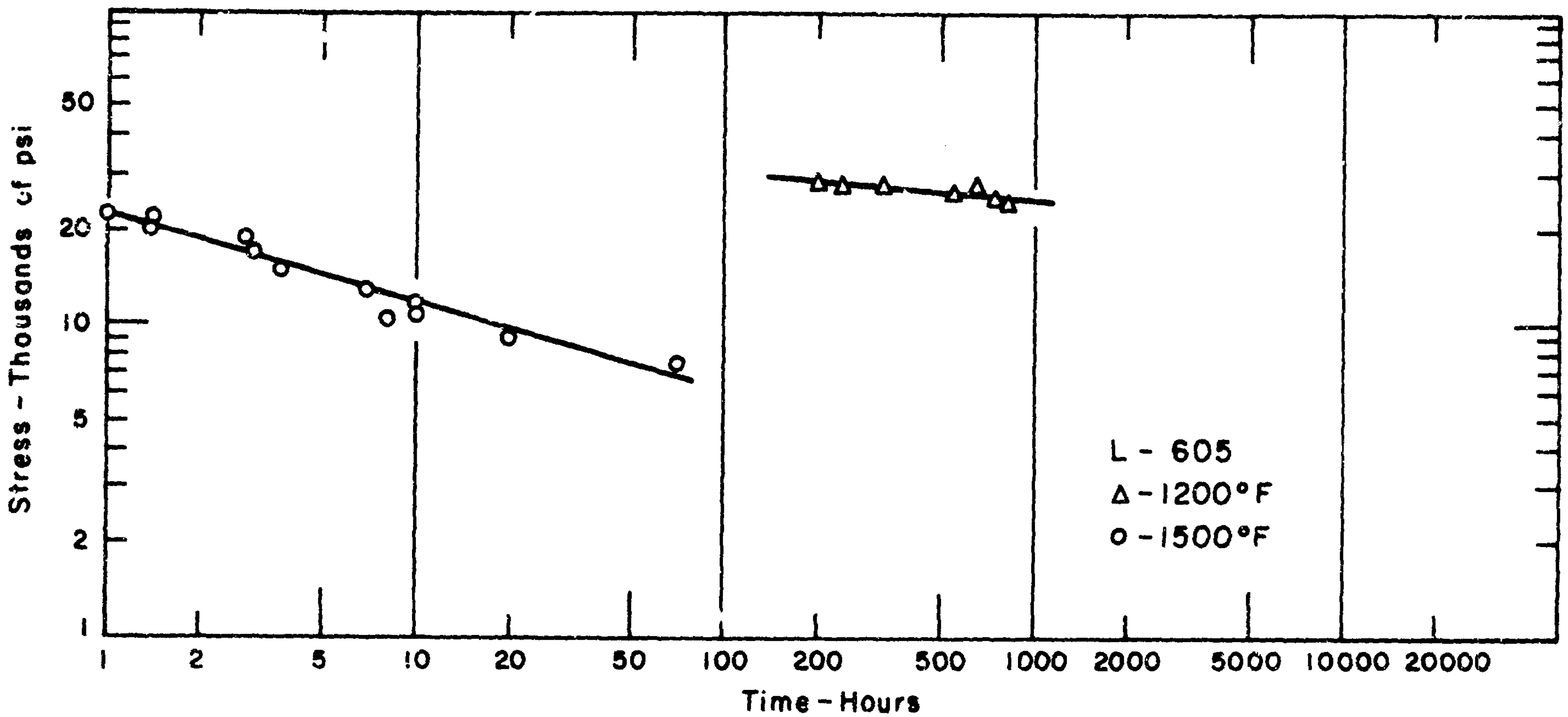


Figure 8. Log stress versus log time 0.1% plastic strain for L-605.

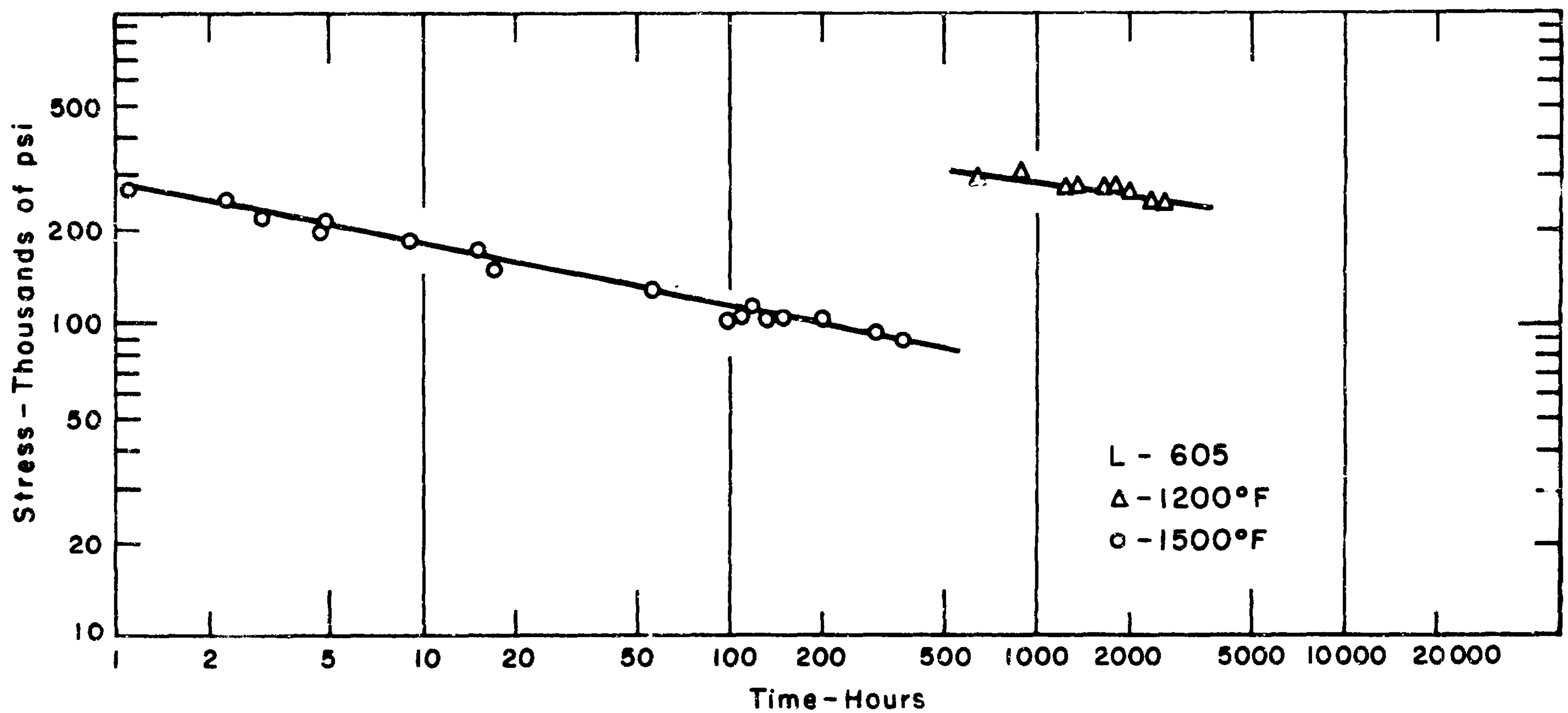


Figure 9. Log stress versus log time to 0.5% plastic strain for L-605.

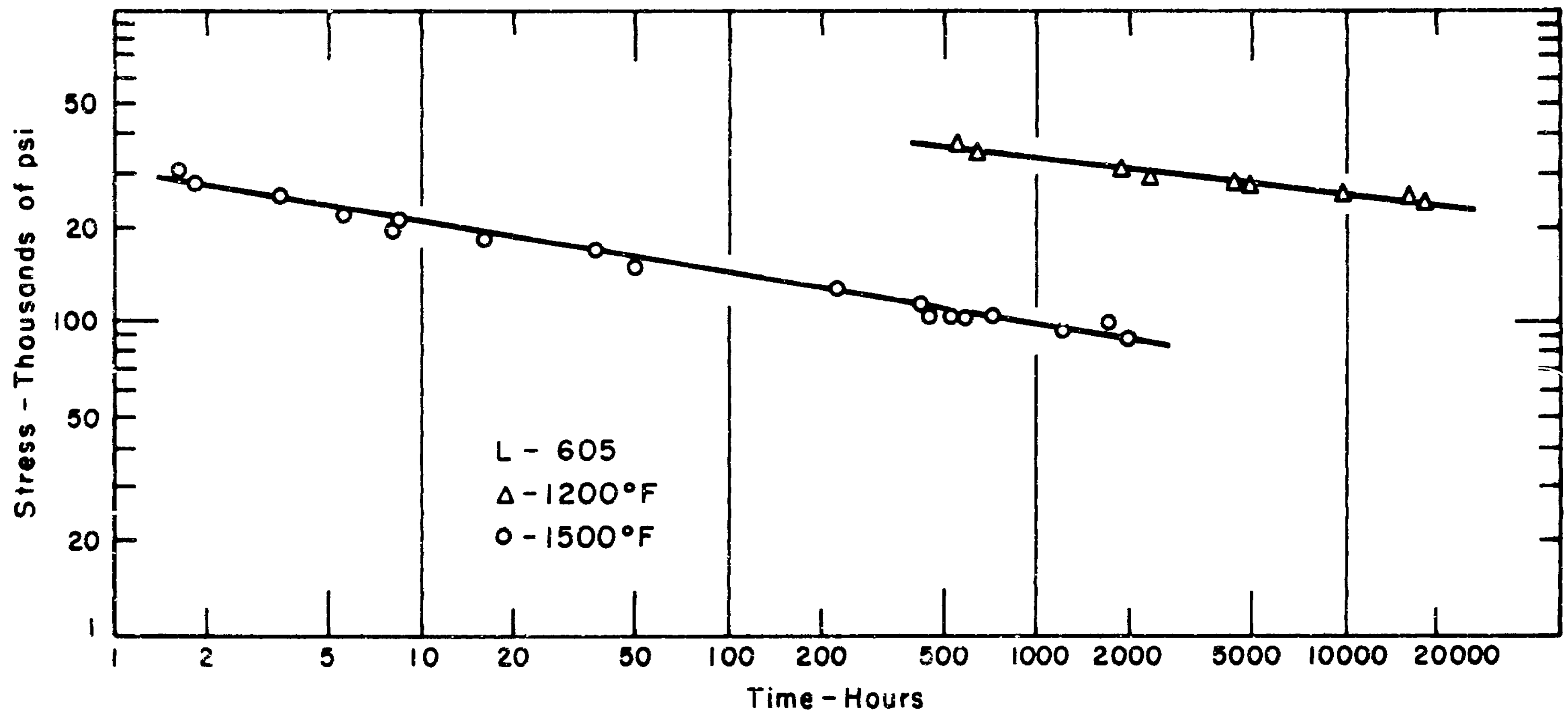


Figure 10. Log stress versus log time to 1.0% plastic strain for L-605.

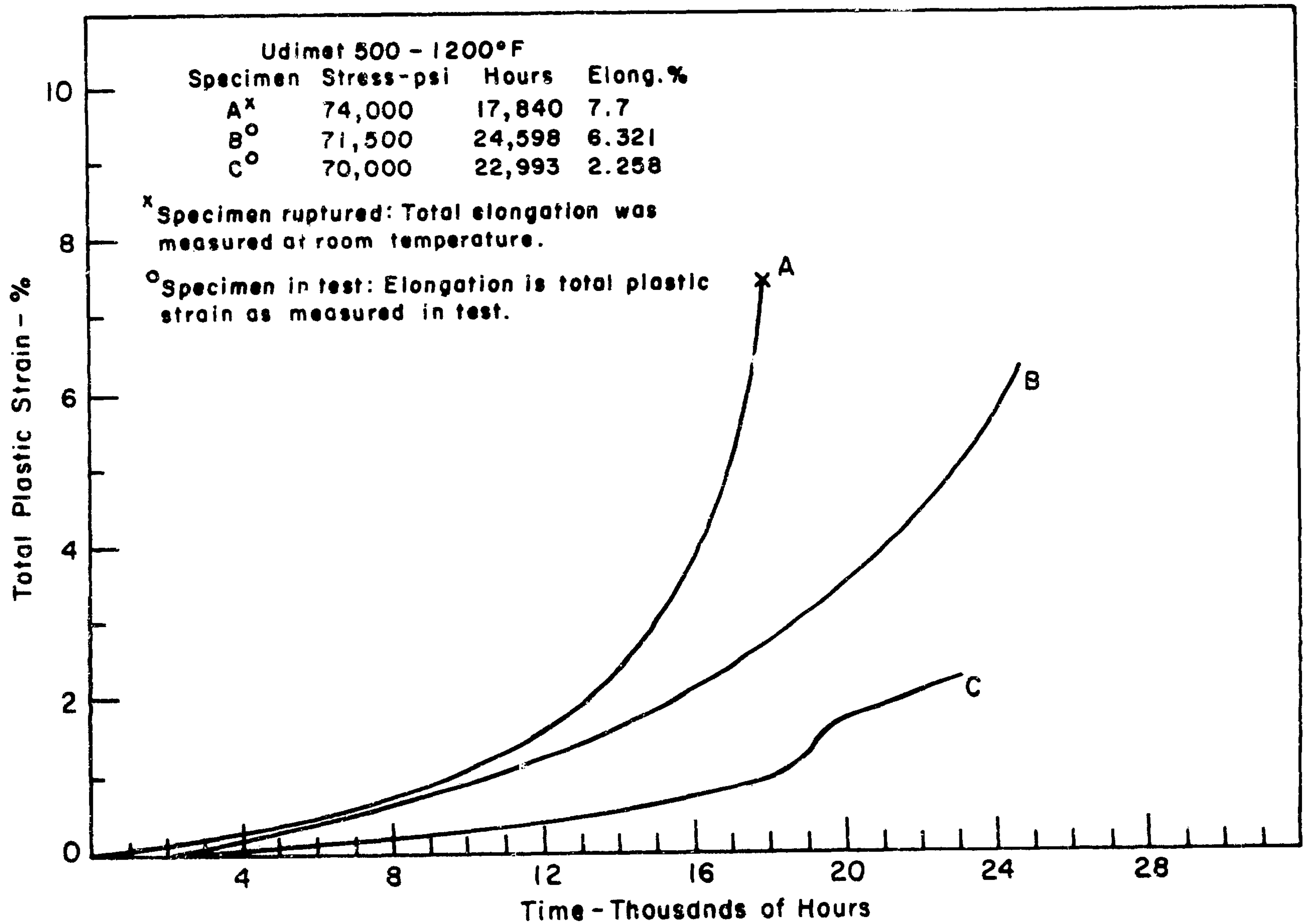


Figure 11. Long time creep curves for Udimet 500 at 1200°F.

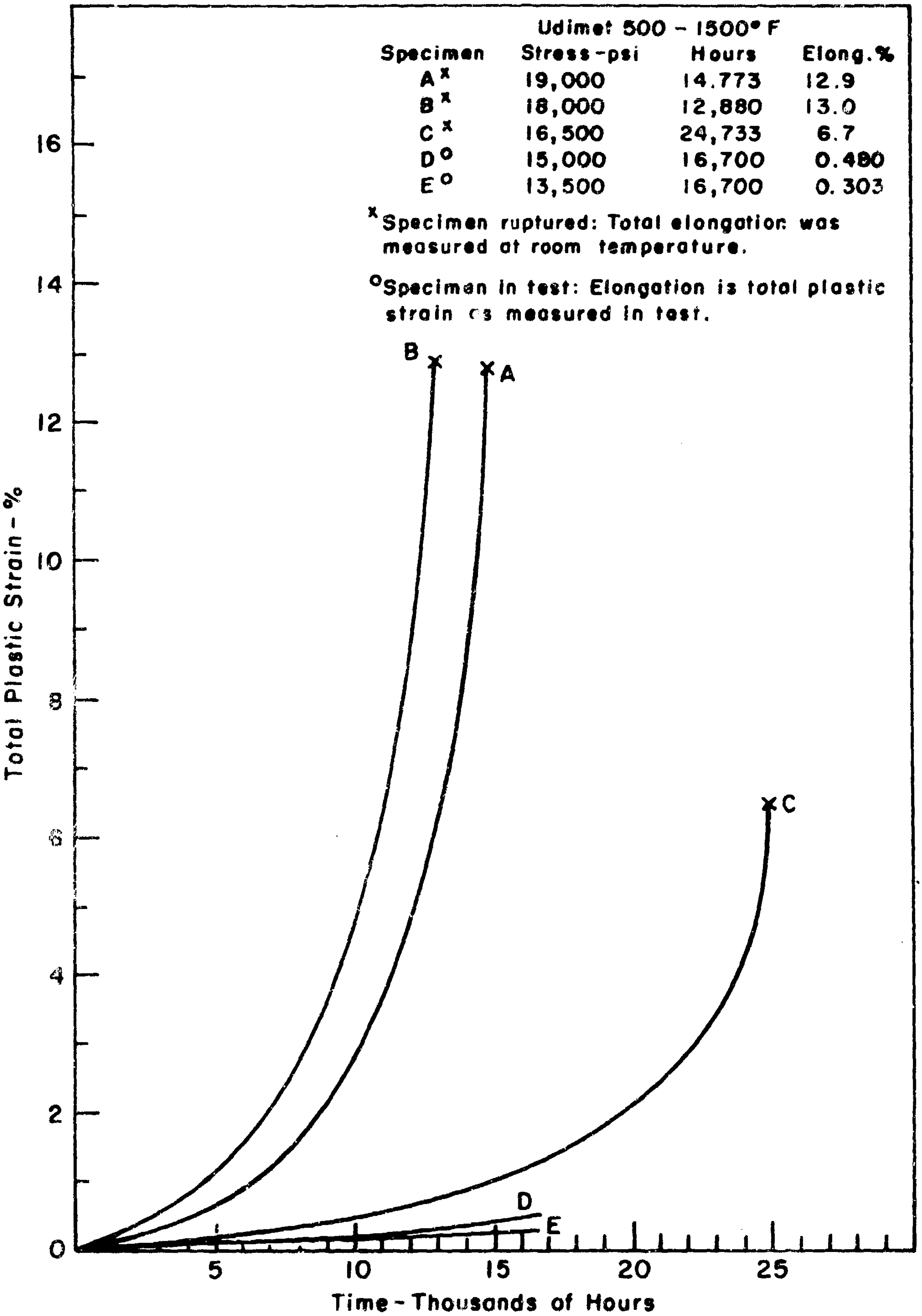


Figure 12. Long time creep curves for Udimet 500 at 1500°F.

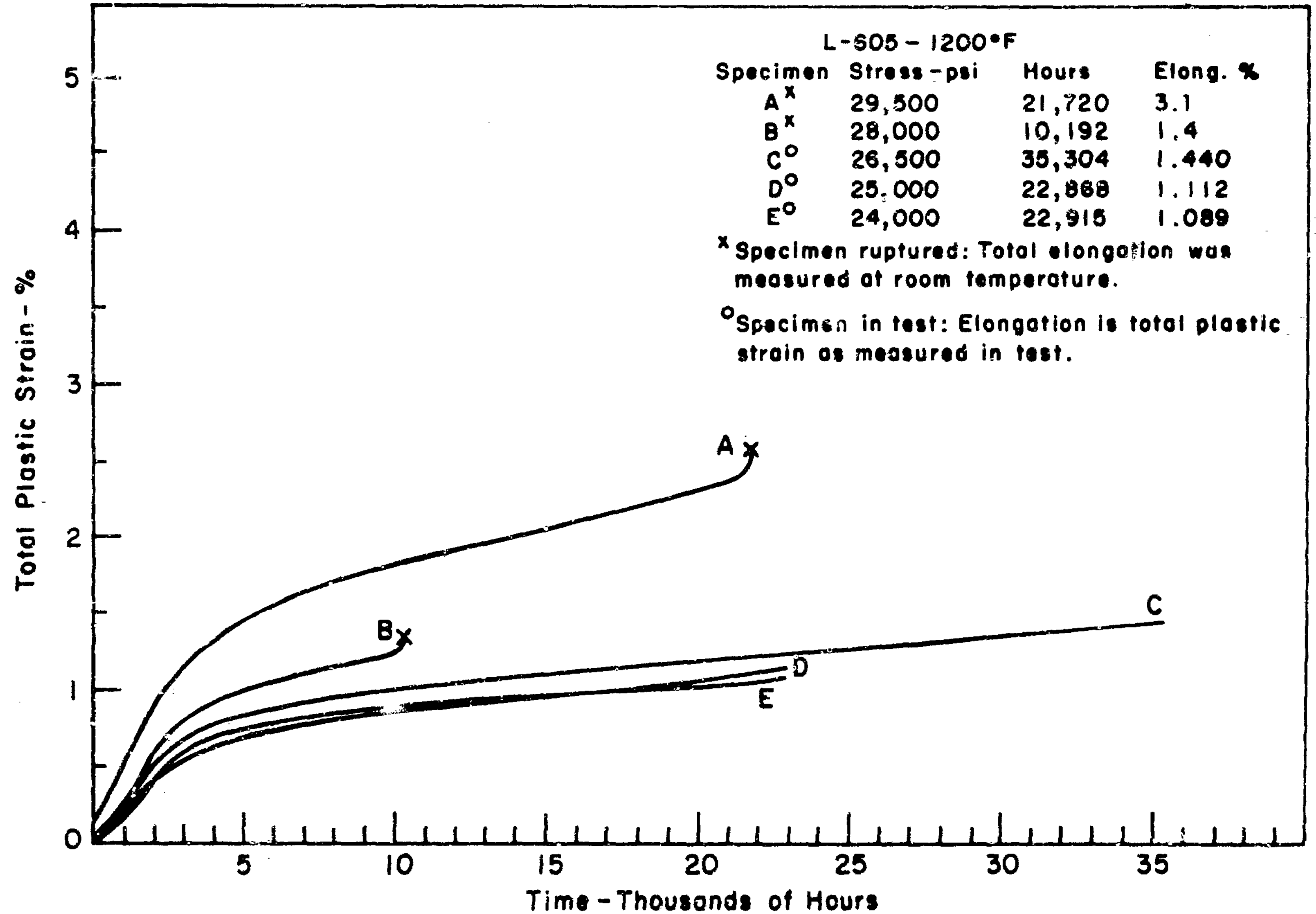


Figure 13. Long time creep curves for L-605 at 1200 °F.

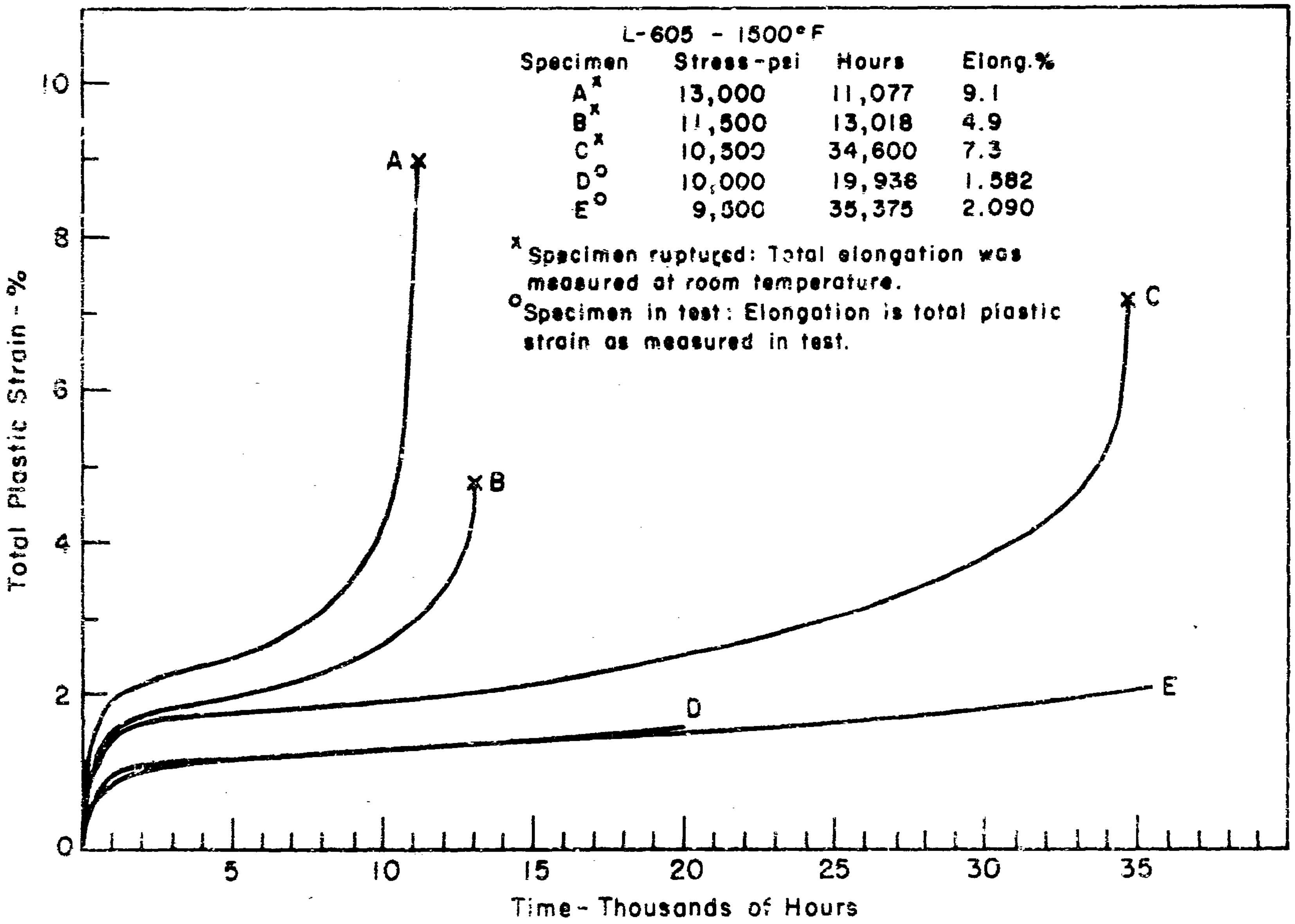
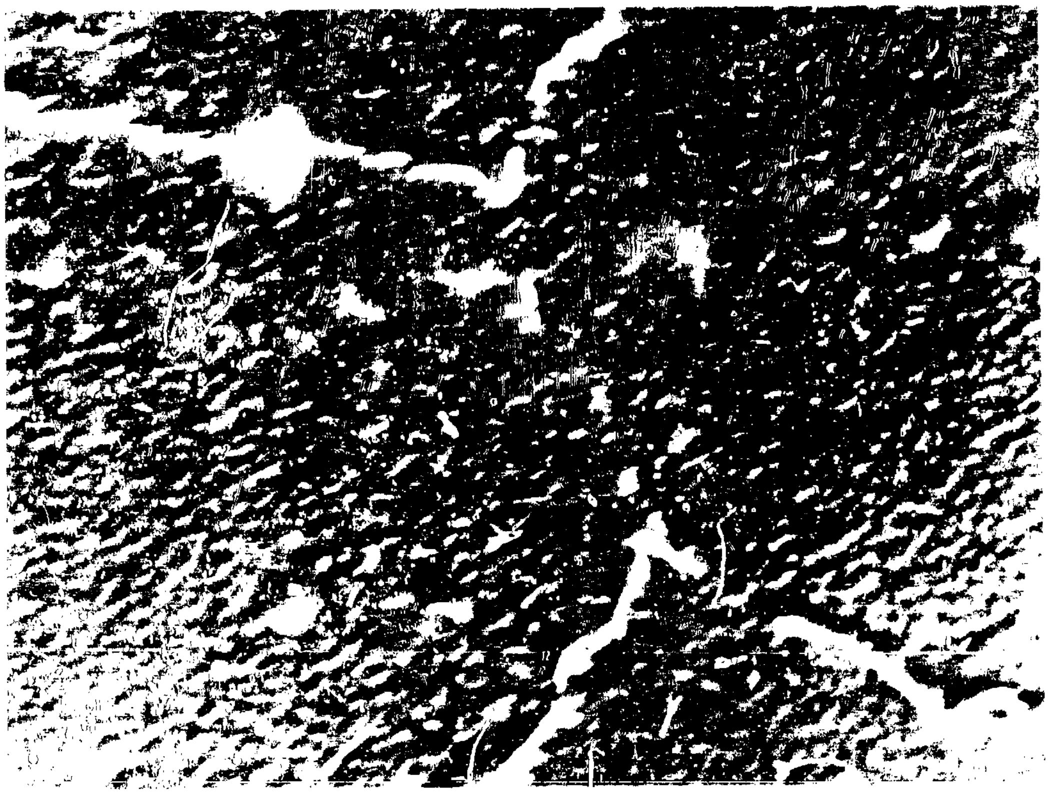


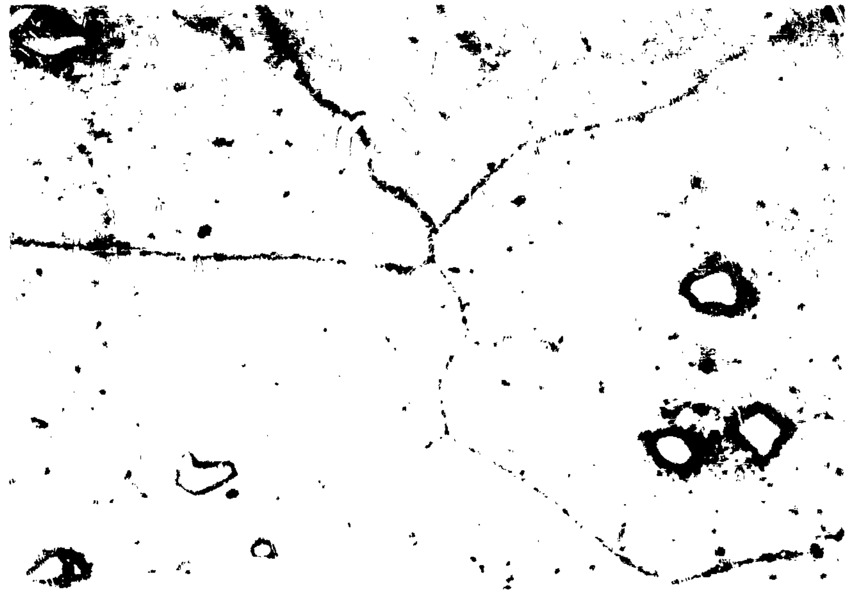
Figure 14. Long time creep curves for L-605 at 1500°F.

Photomicrograph 1000X

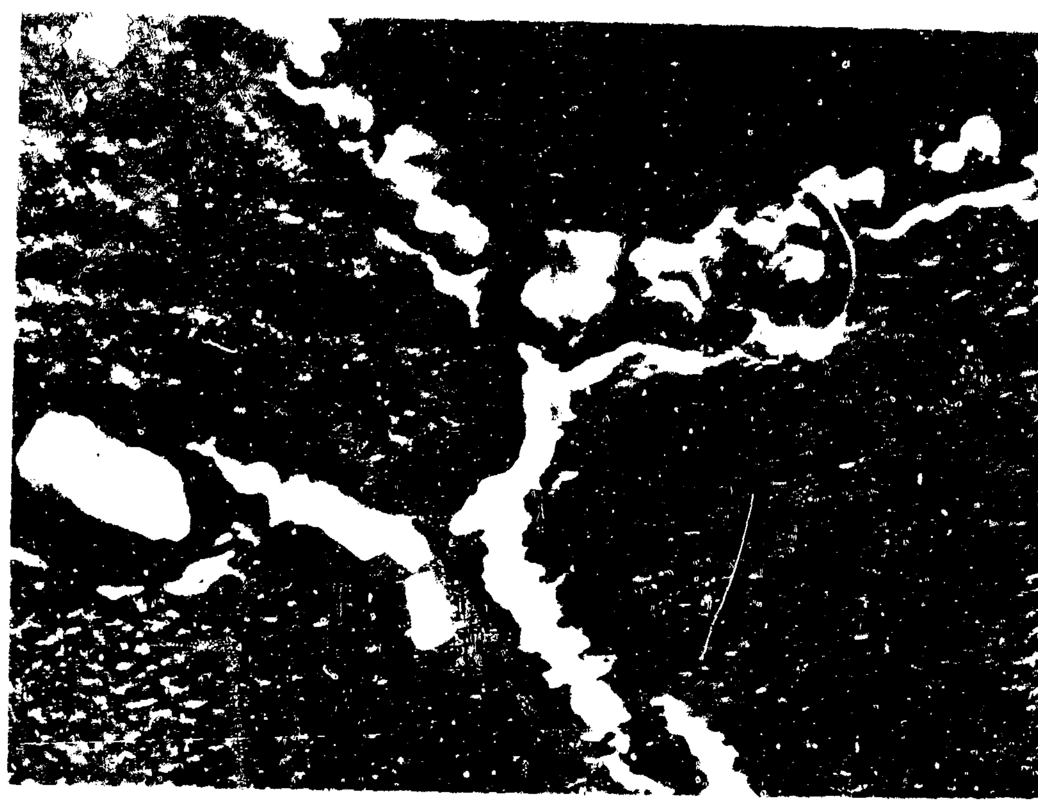


Electron Micrograph 15,000X

Figure 15. Microstructures of Udimet 500. As received, aged condition.



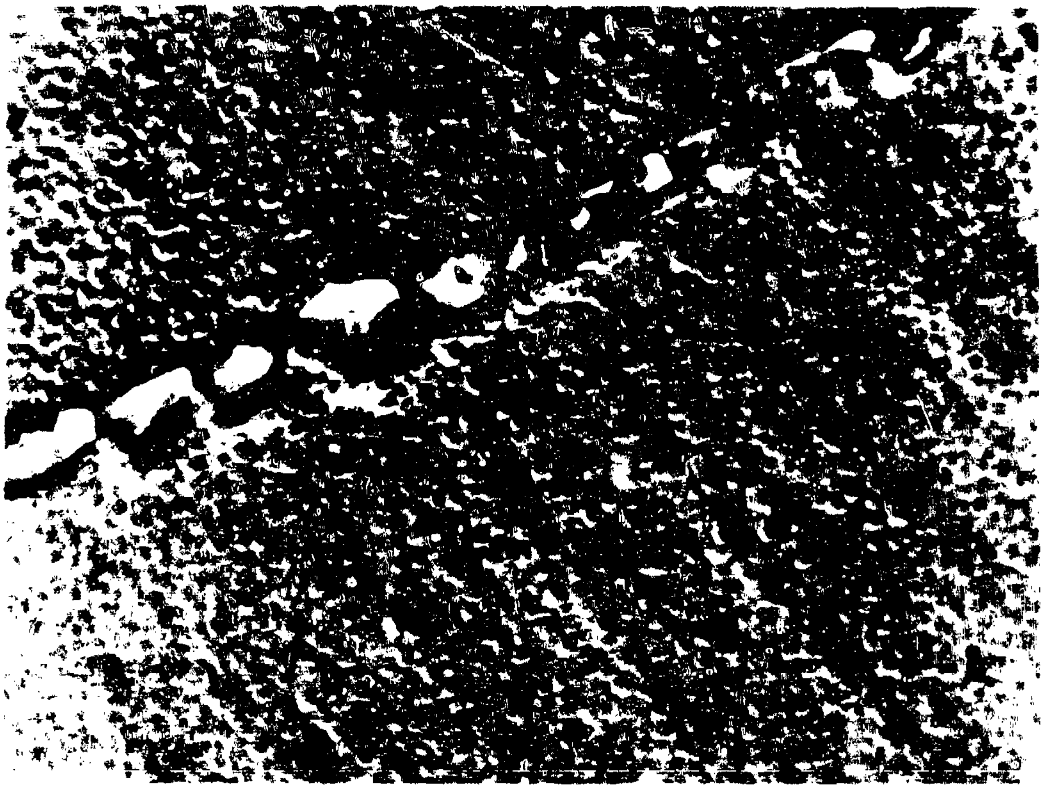
Photomicrograph 1000X



Electron Micrograph 15,000X

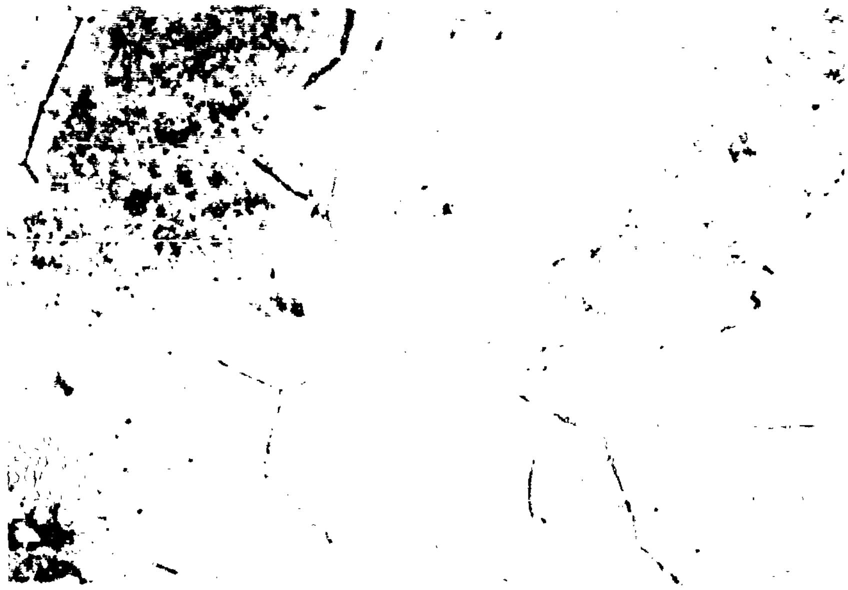
Figure 16. Microstructures of Udimet 500 specimen after test at 1200° F and 140,000 psi. Rupture life, 8.0 hours.

Photomicrograph 1000X

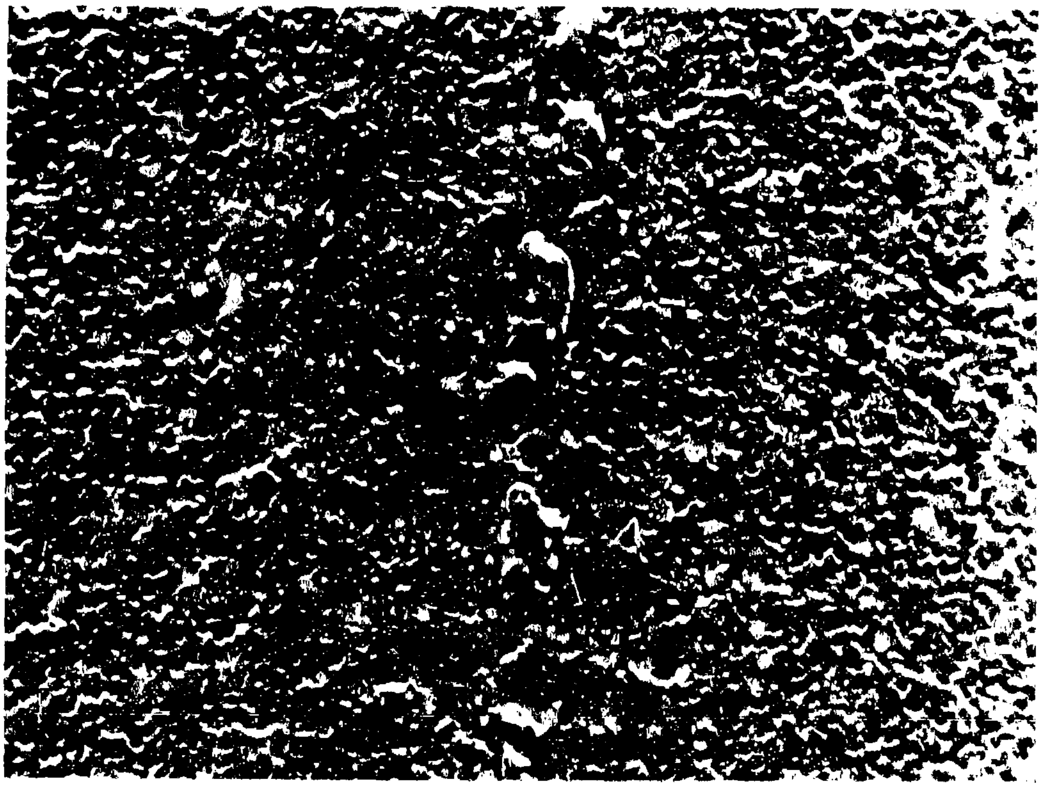


Electron Micrograph 15,000X

Figure 17. Microstructures of Udimet 500 specimen after test at 1200° F and 130,000 psi. Rupture life, 18.3 hours.

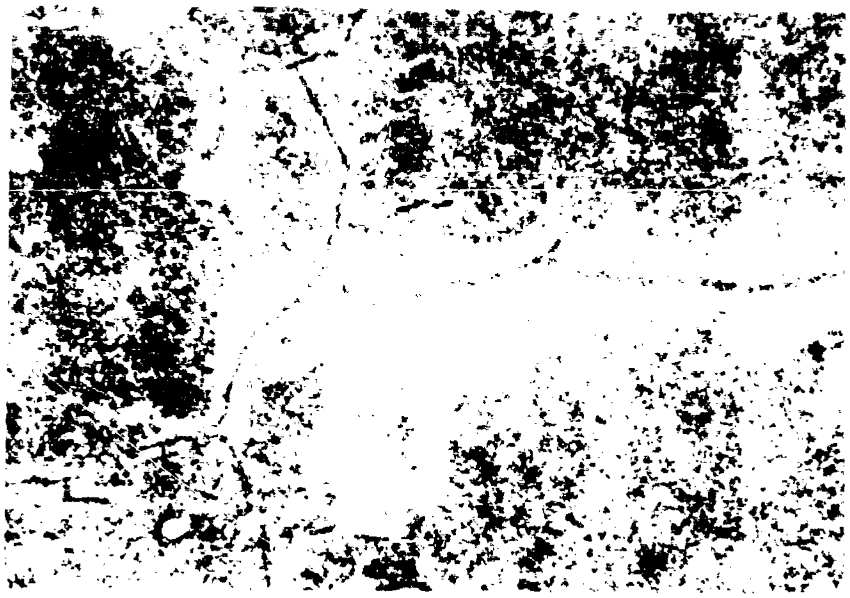


Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 18. Microstructures of Udimet 500 specimen after test at 1200° F and 122,000 psi. Rupture life 37.6 hours.



Photomicrograph 1000X

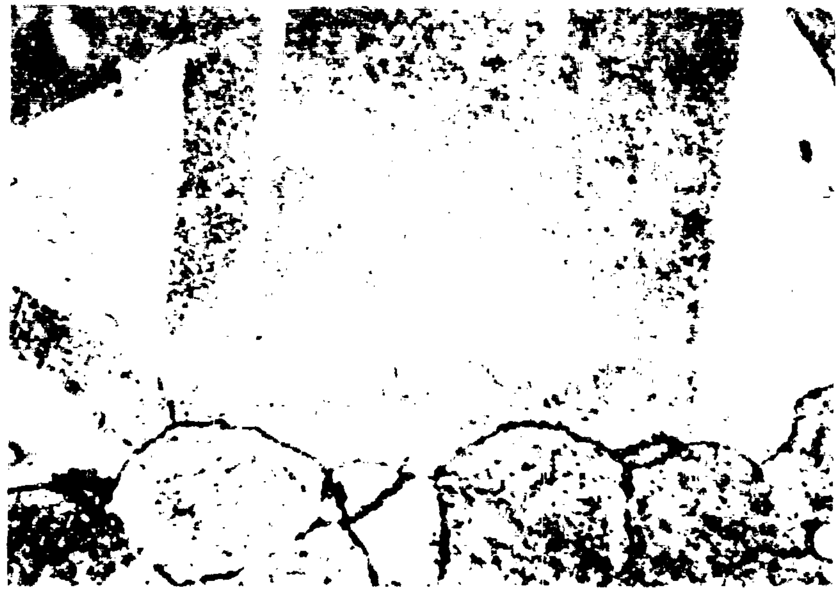
Electron Microgra,h 15,000X

Figure 19. Microstructures of Udimet 500 specimen after test at 1200° F and 117,500 psi. Rupture life 37.0 hours.

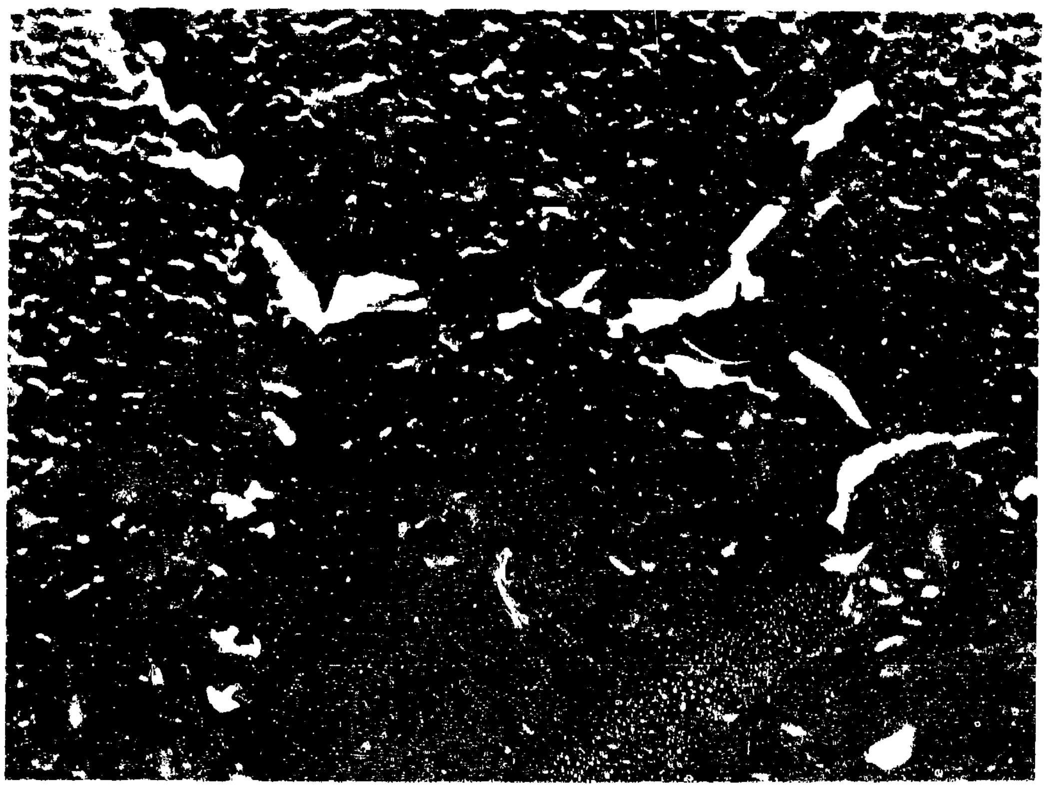
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 20. Microstructures of Udimet 500 specimen after test at 1200° F and 110,000 psi. Rupture life 171.9 hours.



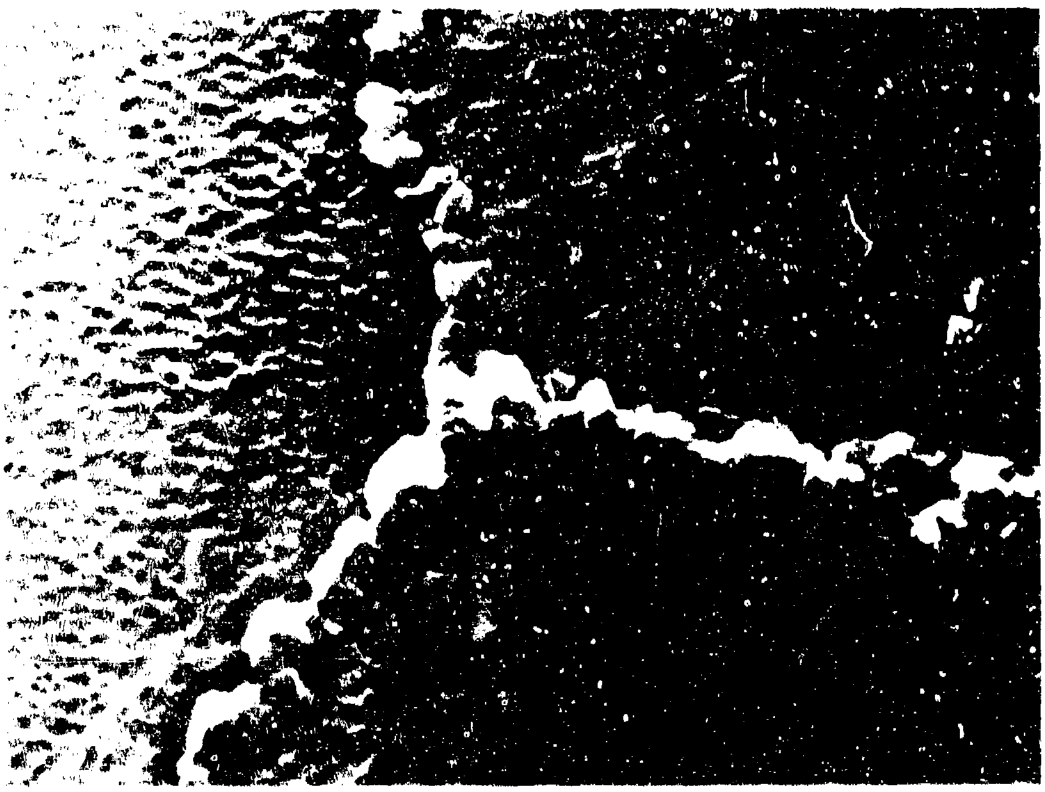
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 21. Microstructures of Udimet 500 specimen after test at 1200° F and 103,000 psi. Rupture life 590.4 hours.

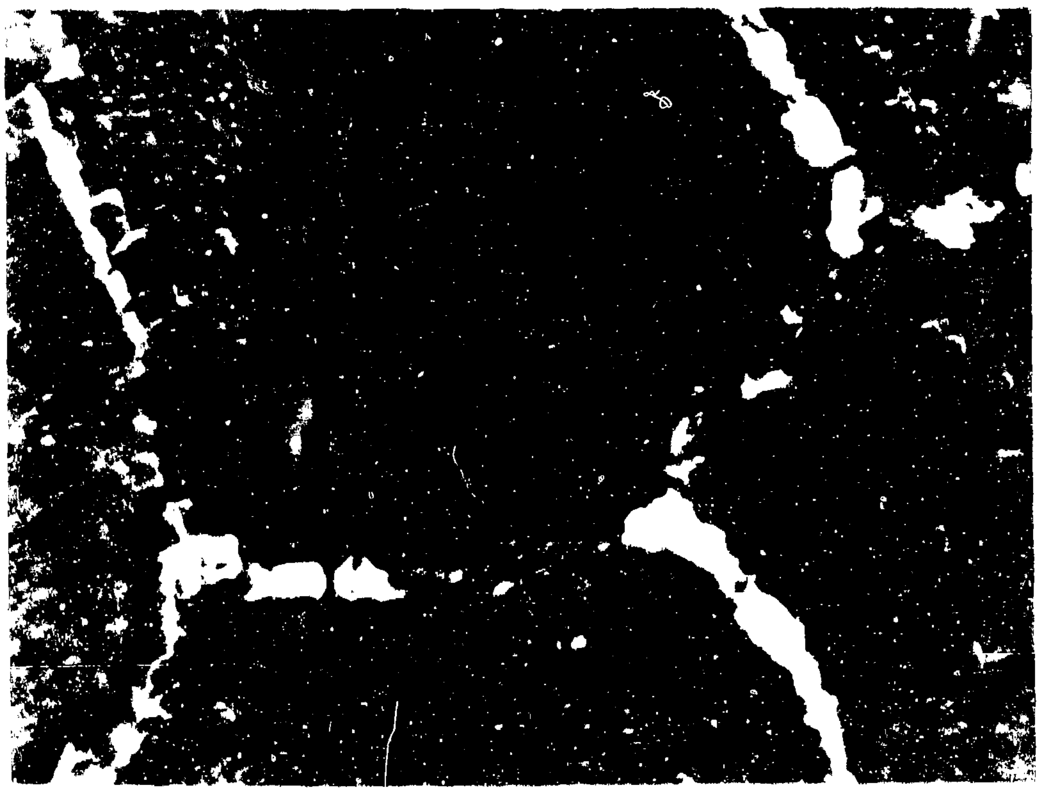
Photomicrograph 1000X



Electron Micrograph 15,000X

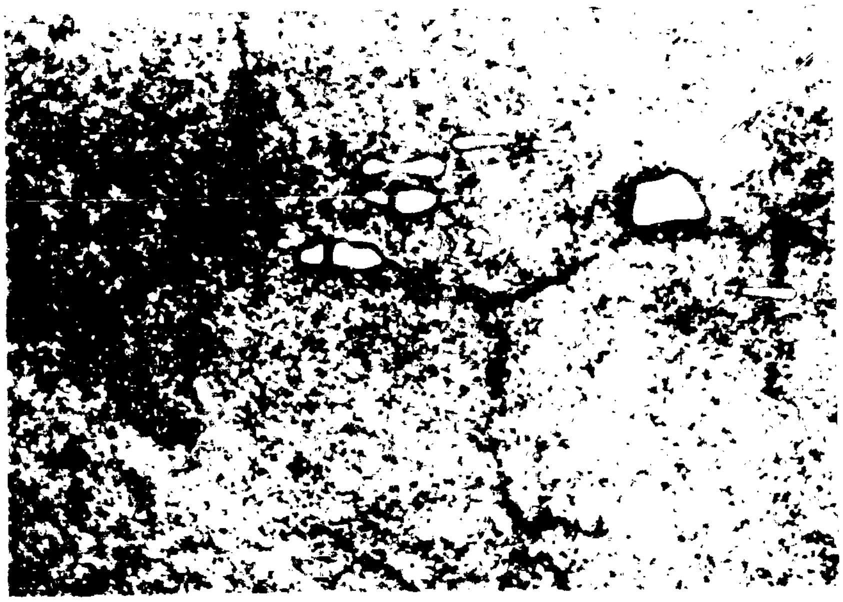
Figure 22. Microstructures of Udimet 500 specimen after test at 1200° F and 100,000 psi. Rupture life 427.4 hours.

Photomicrograph 1000X

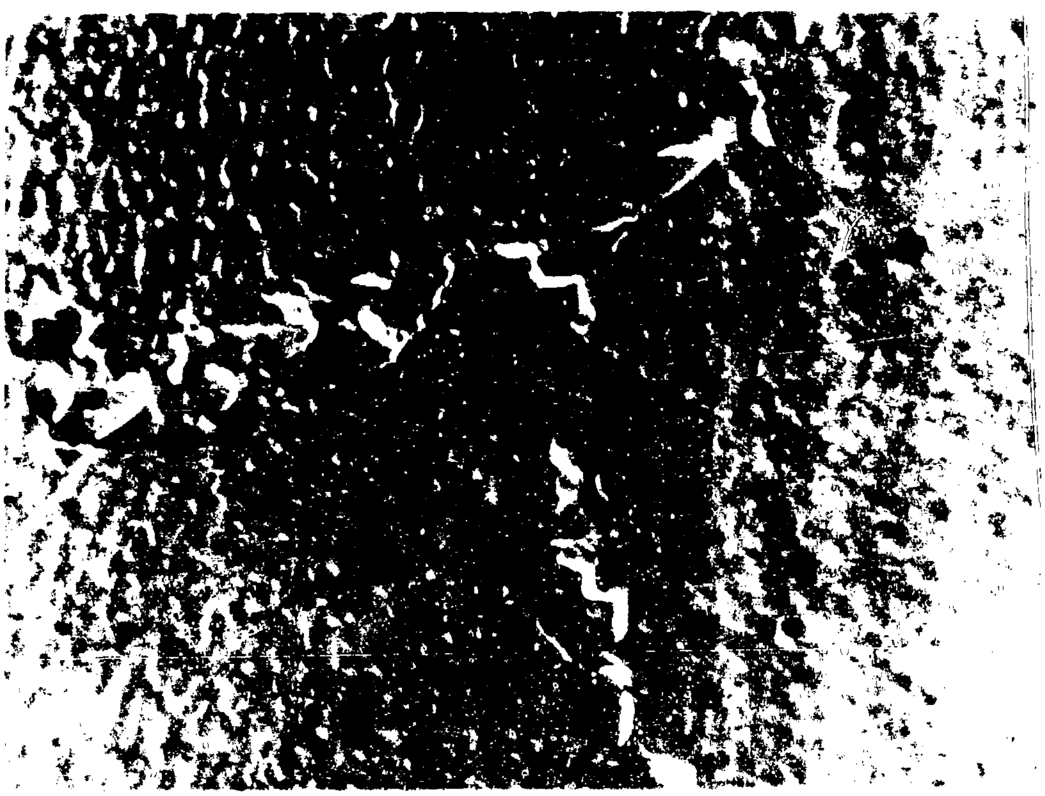


Electron Micrograph 15,000X

Figure 23. Microstructures of Udimet 500 specimen after test at 1200° F and 95,000 psi. Rupture life 1396.3 hours.

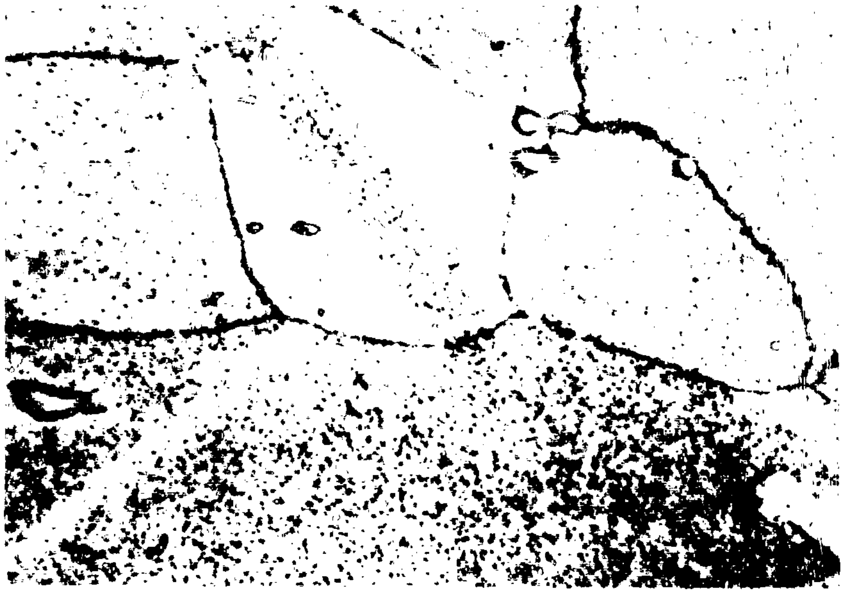


Photomicrograph 1000X

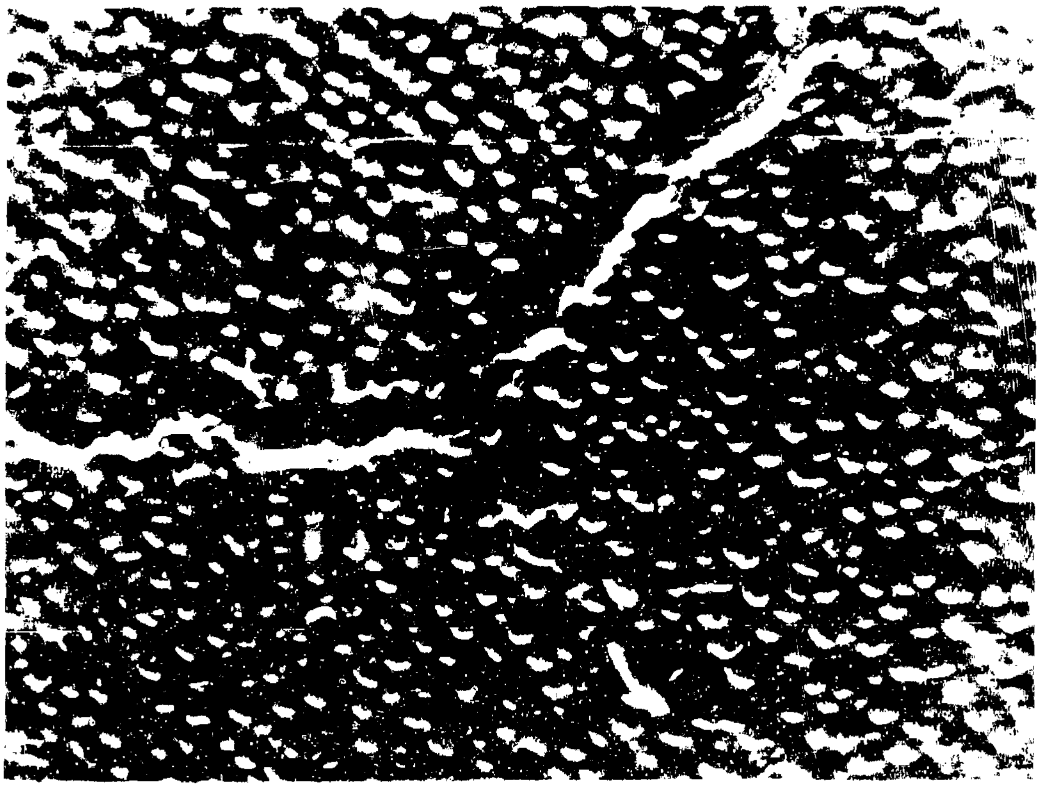


Electron Micrograph 15,000X

Figure 24. Microstructures of Udimet 500 specimen after test at 1200° F and 90,000 psi. Rupture life 4428.9 hours.

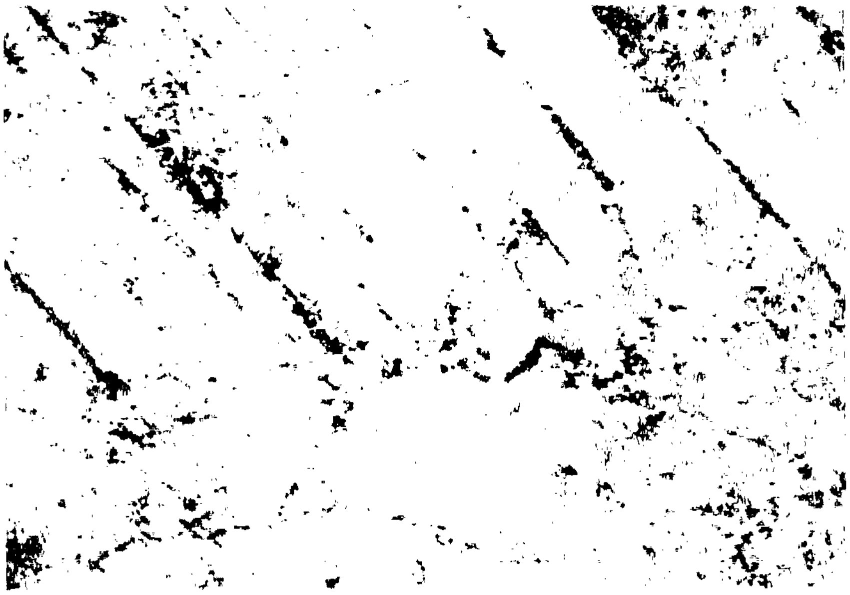


Photomicrograph 1000X



Electron Micrograph 15,000X

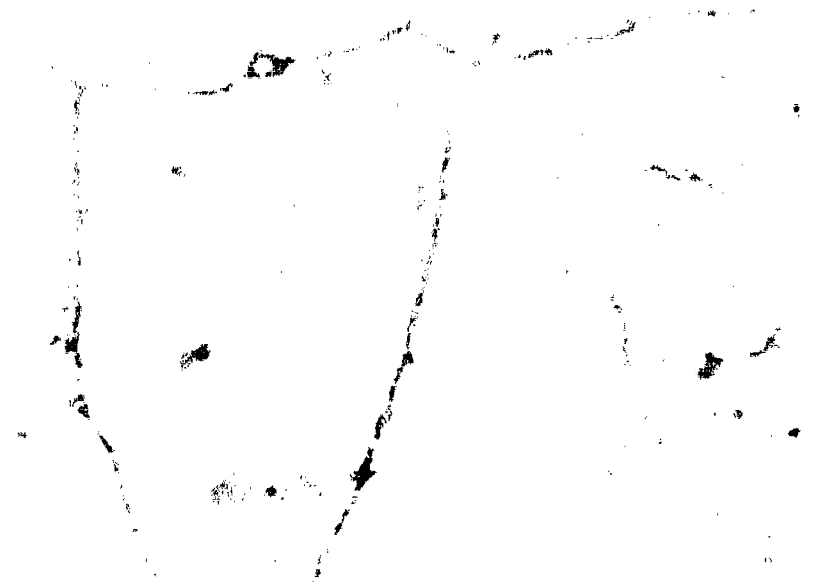
Figure 25. Microstructures of Udimet 500 specimen after test at 1200° F and 86,000 psi. Rupture life 4041.5 hours.



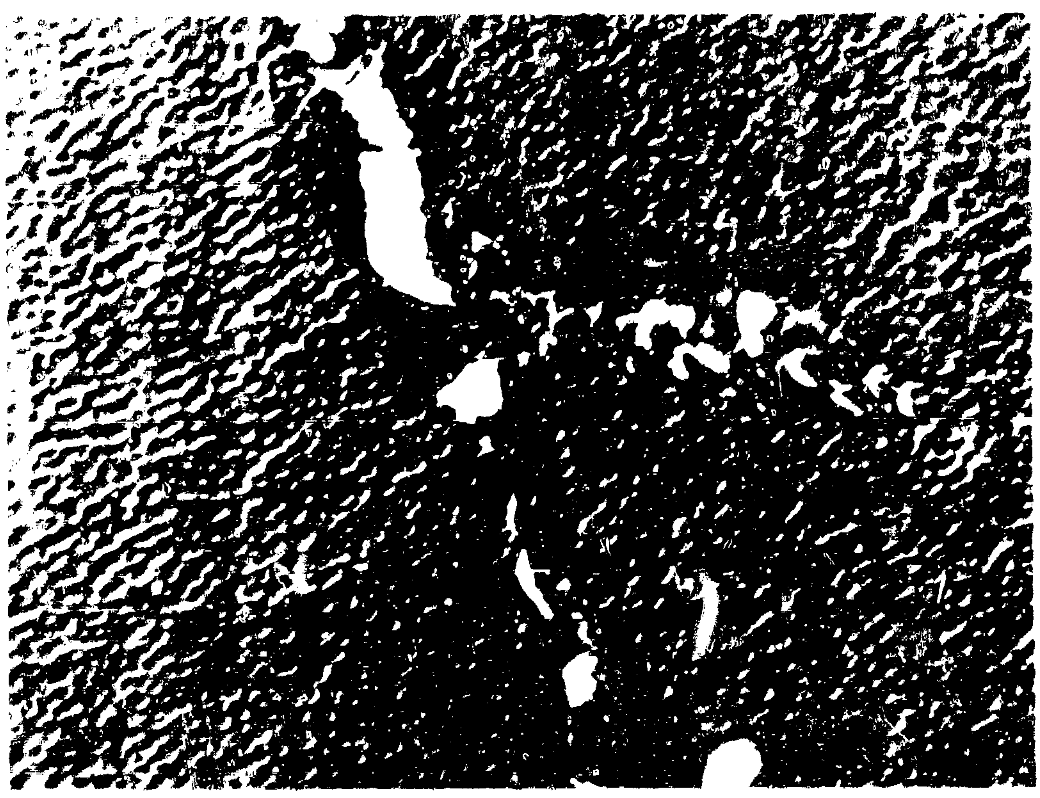
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 26. Microstructures of Udimet 500 specimen after test at 1200° F and 80,000 psi. Rupture life 9724.5 hours.



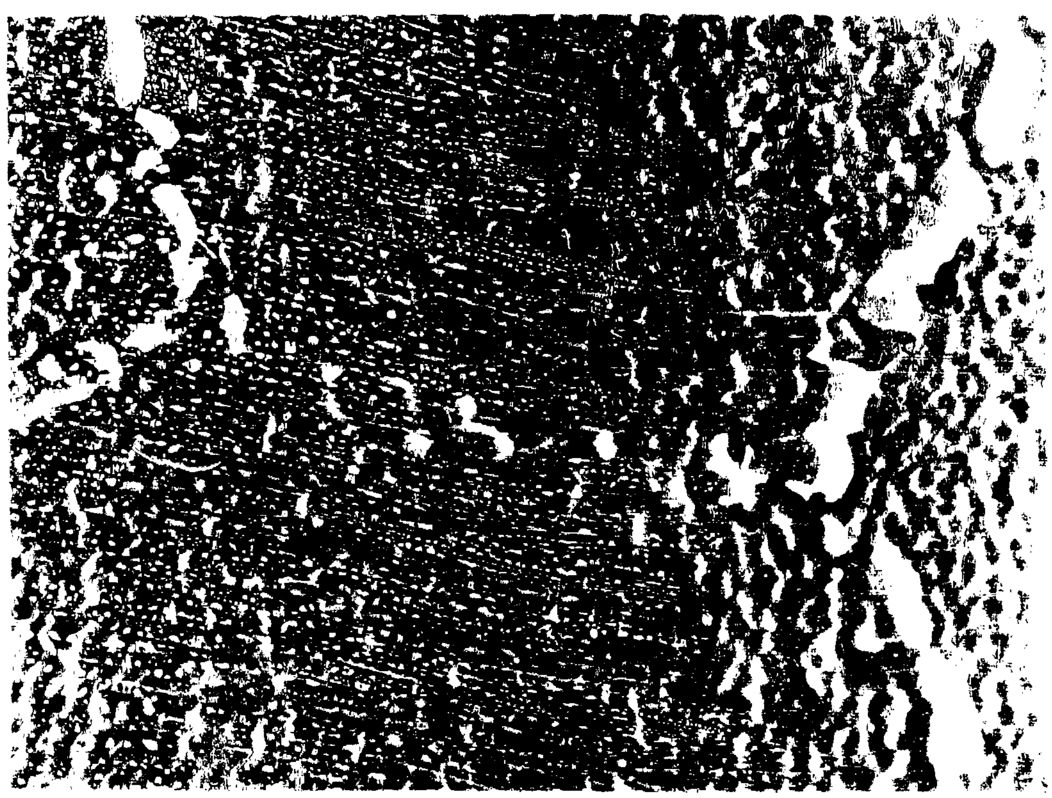
Photomicrograph 1000X



Electron Micrograph 15,000X

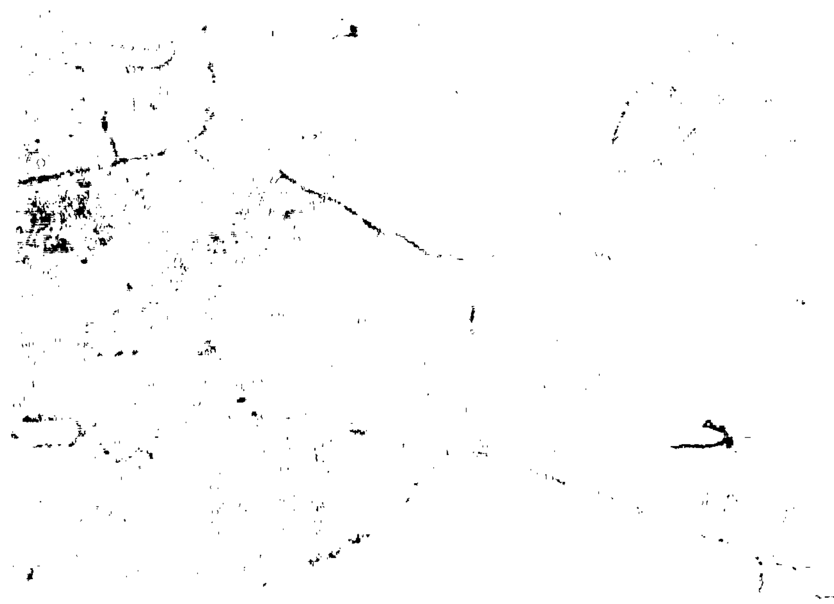
Figure 27. Microstructures of Udimet 500 specimen after test at 1200° F and 77,000 psi. Rupture life 9152.8 hours.

Photomicrograph 1000X

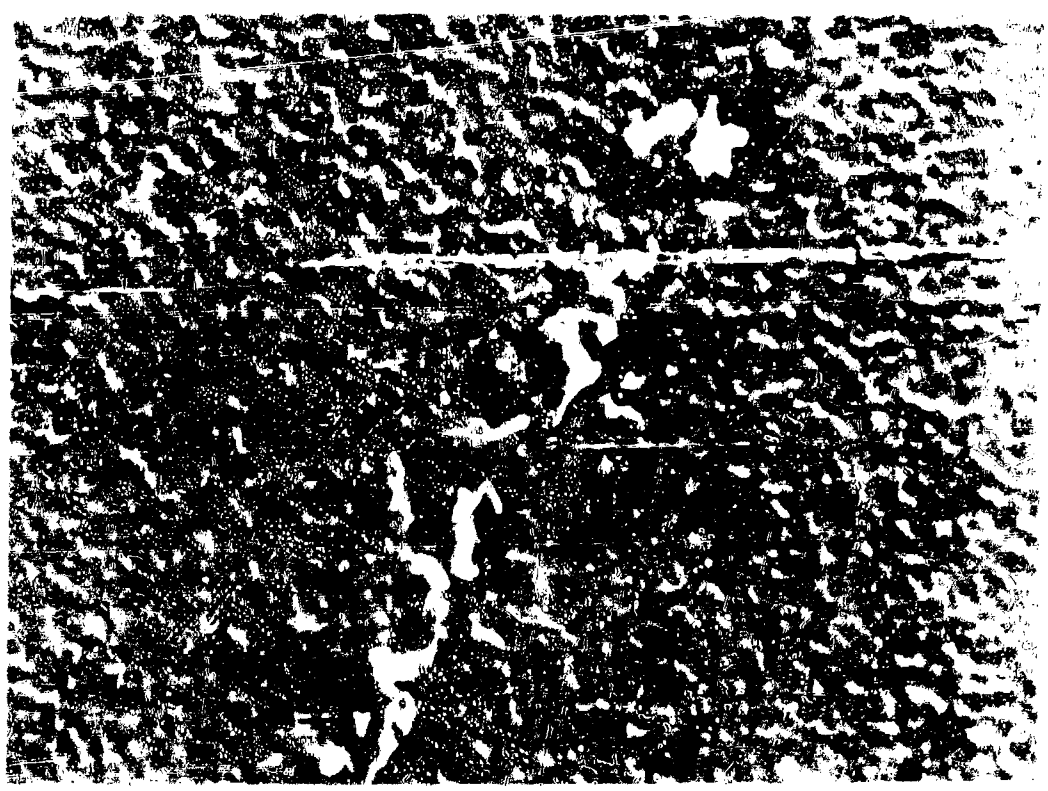


Electron Micrograph 15,000X

Figure 28. Microstructures of Udimet 500 specimen after test at 1200° F and 74,000 psi. Rupture life 17,840 hours.

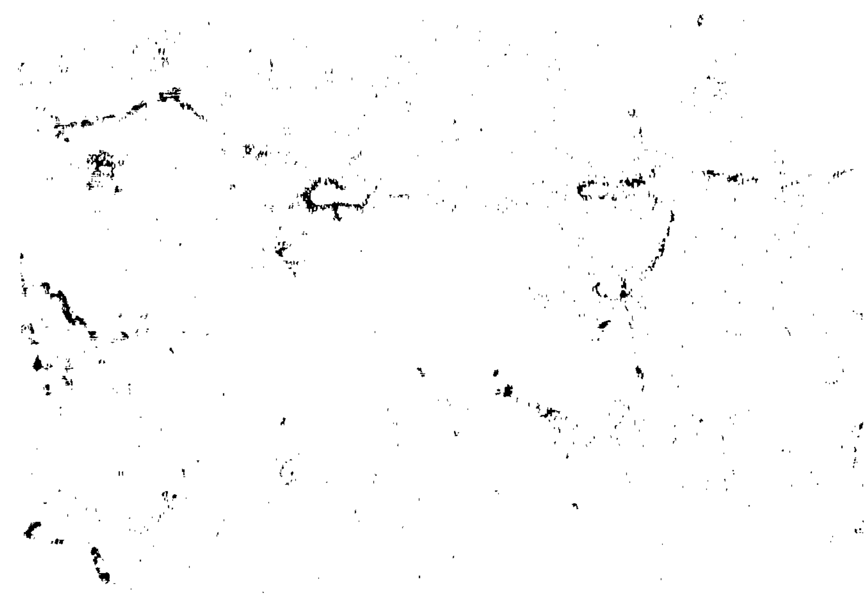


Photomicrograph 1000X



Electron Micrograph 15,000X

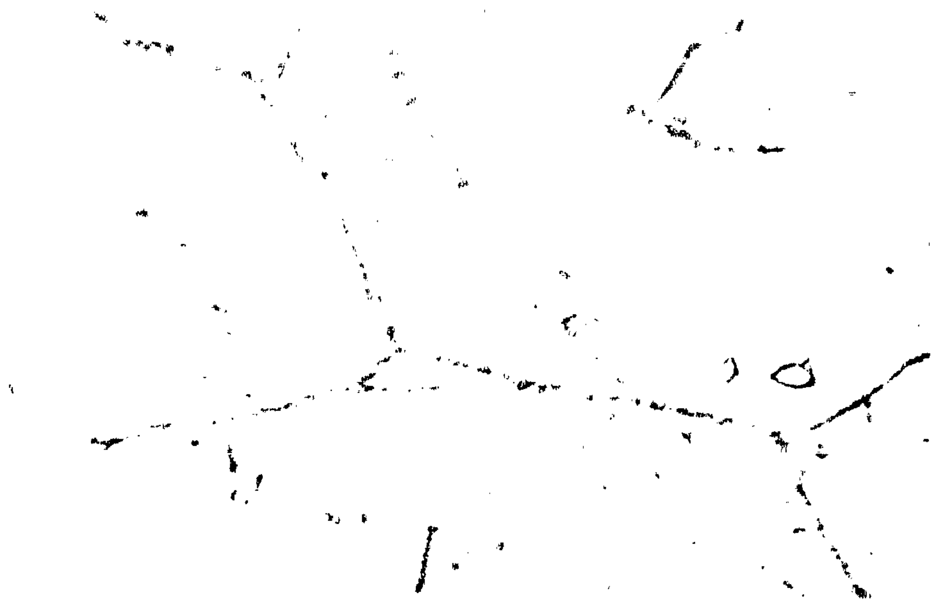
Figure 29. Microstructures of Udimet 500 specimen after test at 1500° F and 80,000 psi. Rupture life 1.7 hours.



Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 30. Microstructures of Udimet 500 specimen after test at 1500° F and 72,000 psi. Rupture life 5.0 hours.



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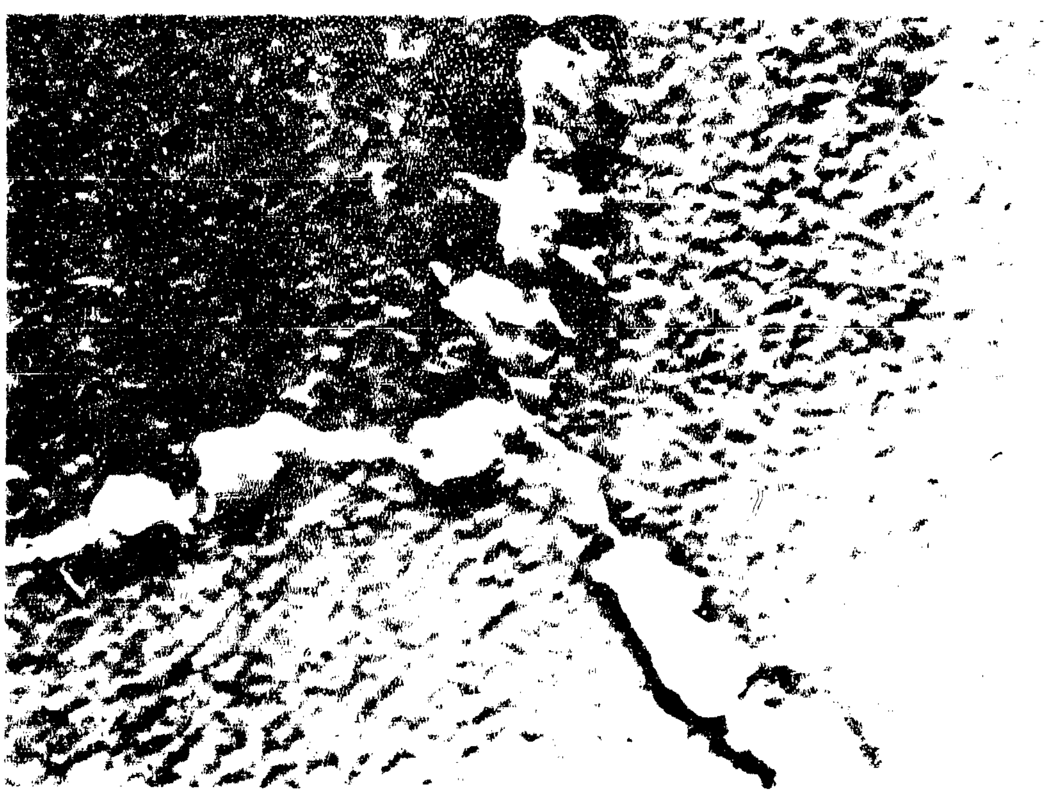
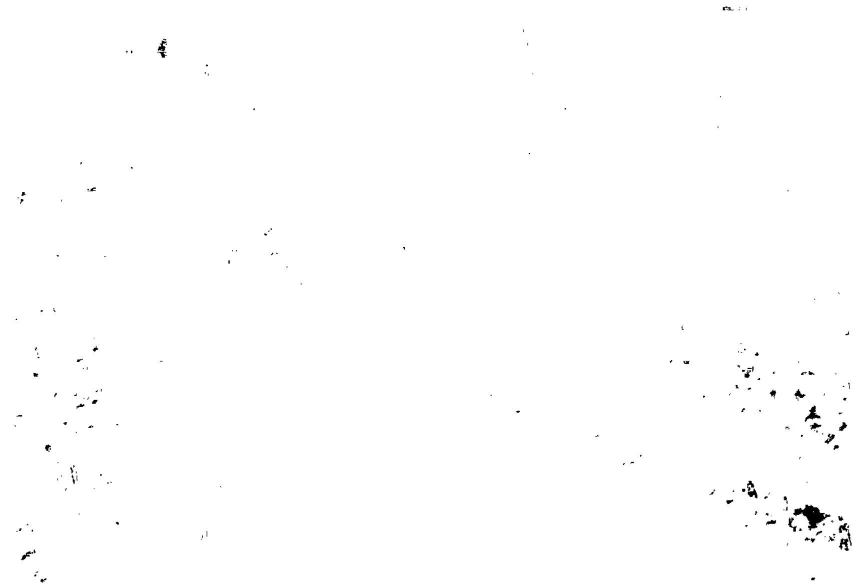


Electron Micrograph 15,000X

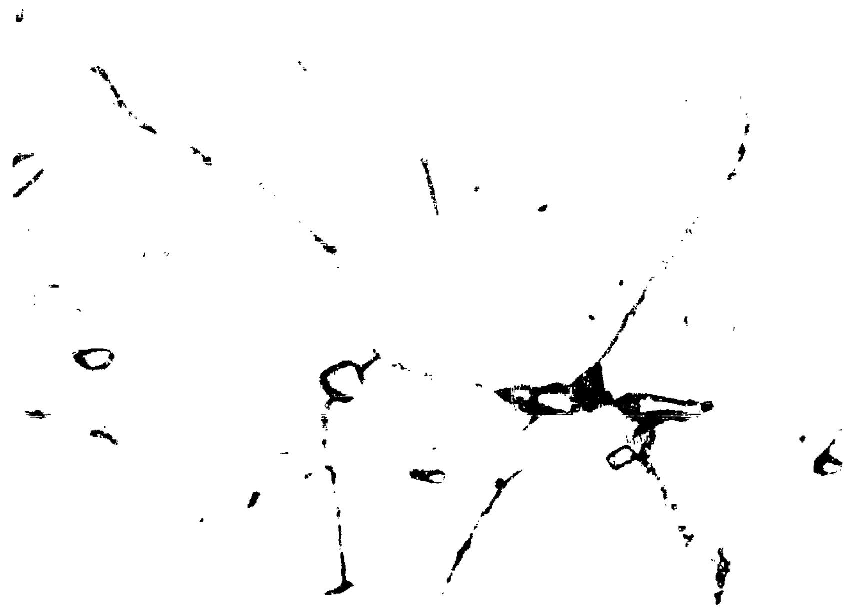
Figure 31. Microstructures of Udimet 500 specimen after test at 1500° F and 60,000 psi. Rupture life 10.5 hours.



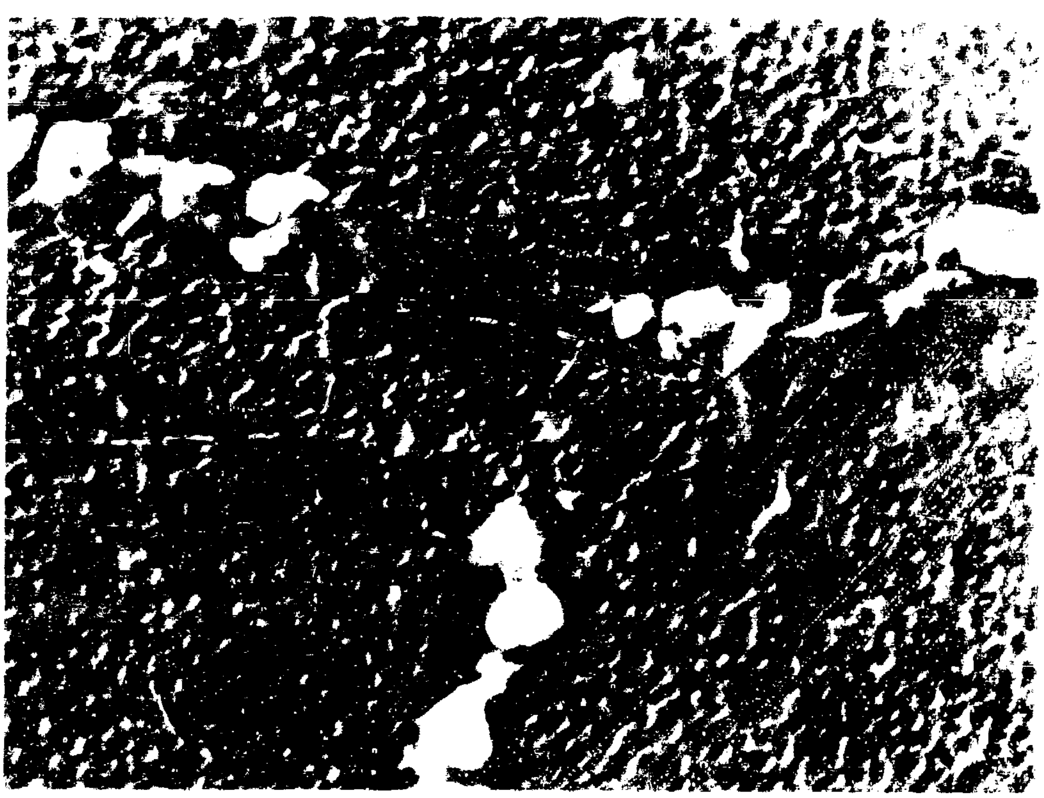
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 32. Microstructures of Udimet 500 specimen after test at 1500° F and 55,000 psi. Rupture life 33.0 hours.

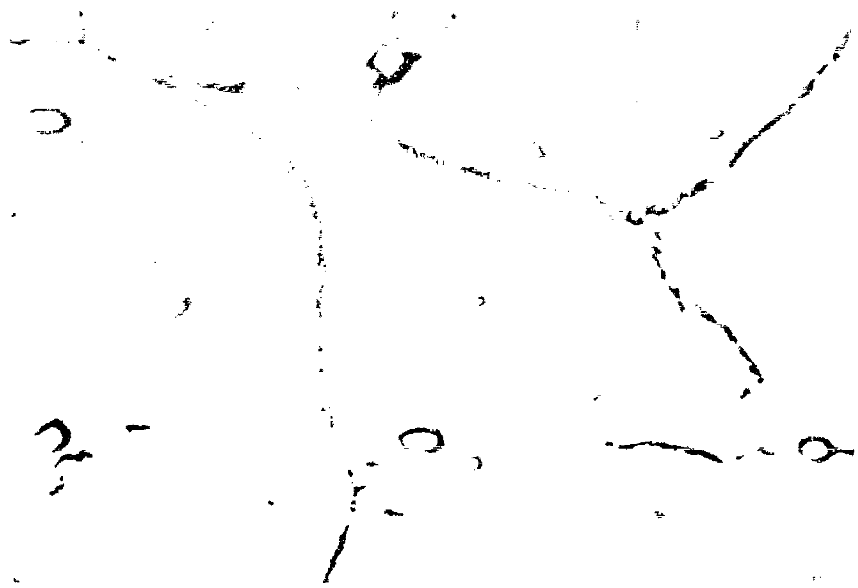


Photomicrograph 1000X

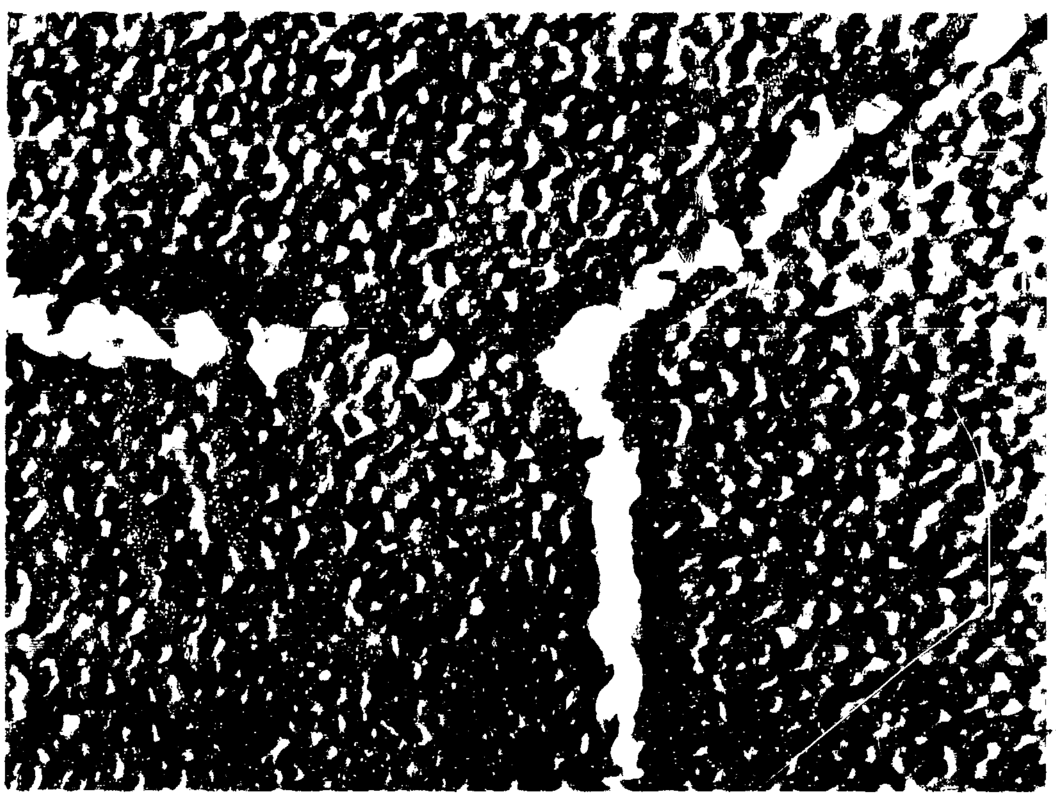


Electron Micrograph 15,000X

Figure 33. Microstructures of Udimet 500 specimen after test at 1500° F and 45,000 psi. Rupture life 159.6 hours.



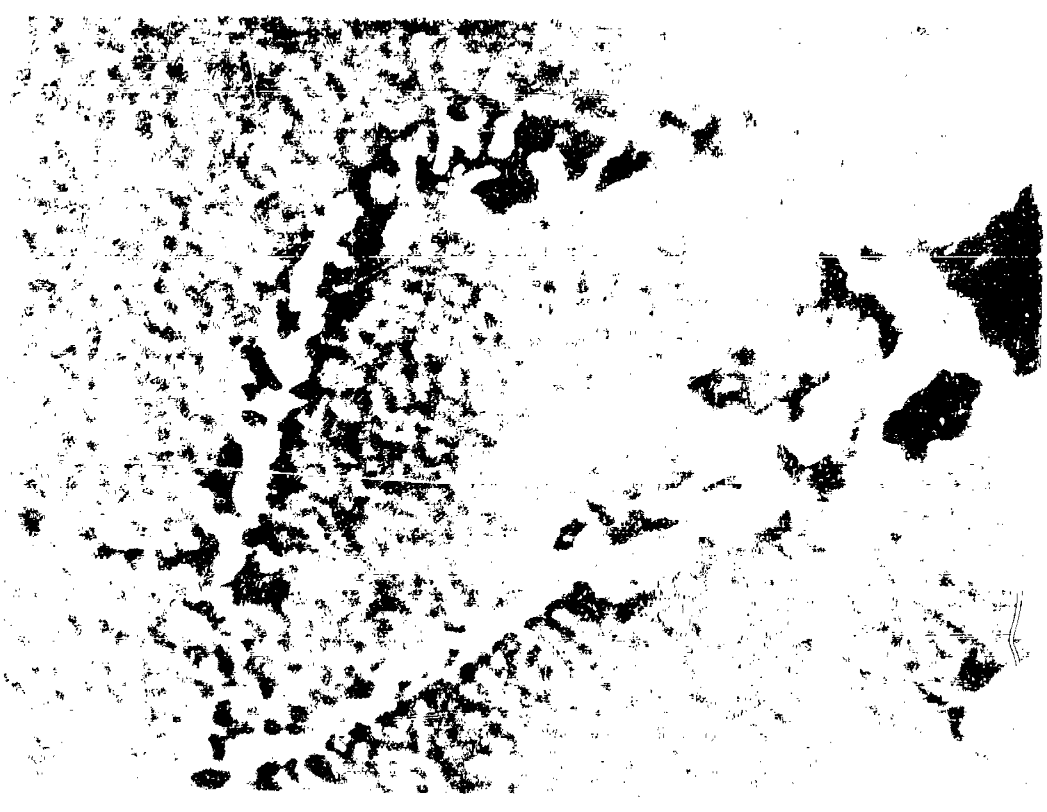
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 34. Microstructures of Udimet 500 specimen after test at 1500° F and 42,500 psi. Rupture life 193.0 hours.

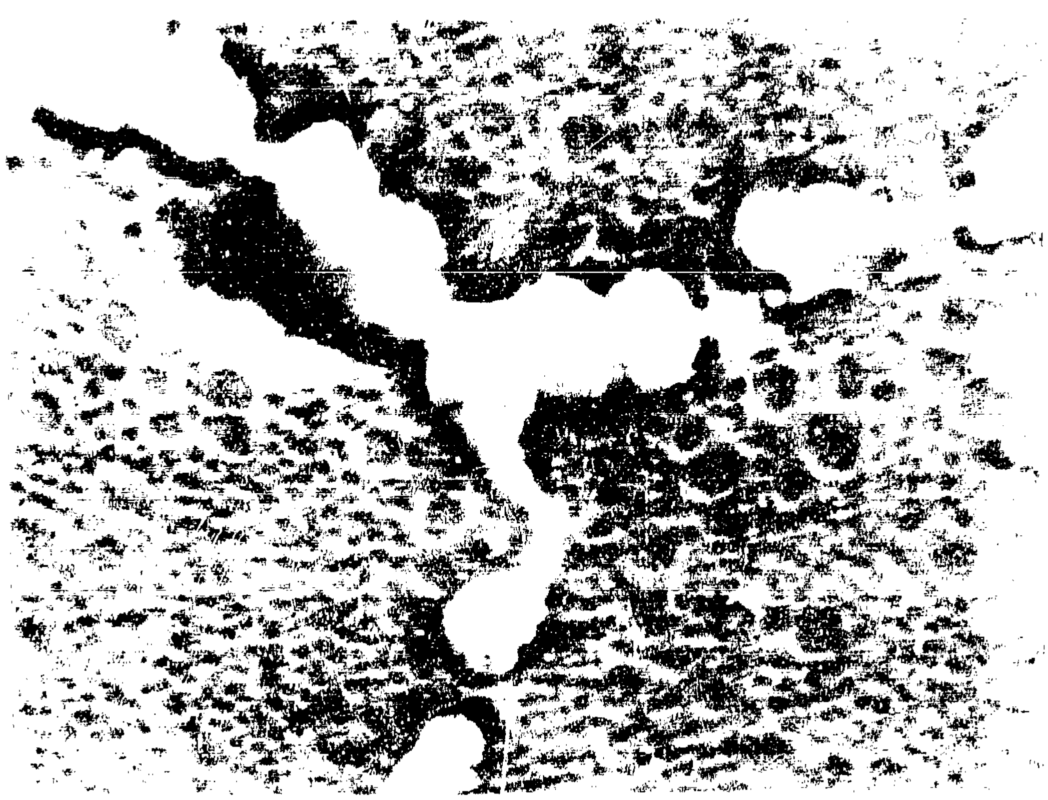
Photomicrograph 1000X



Electron Micrograph 15,000X

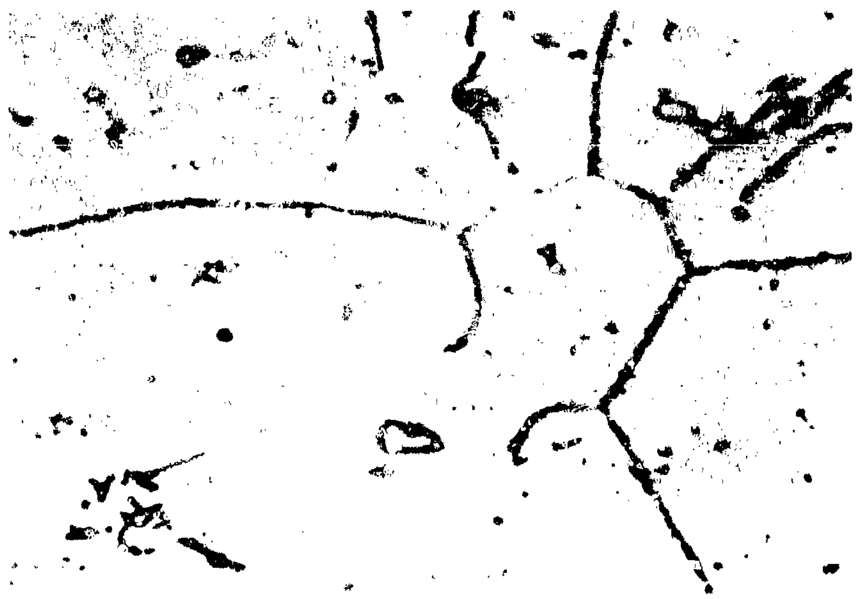
Figure 35. Microstructures of Udimet 500 specimen after test at 1500° F and 39,000 psi. Rupture life 421.2 hours.

Photomicrograph 1000X

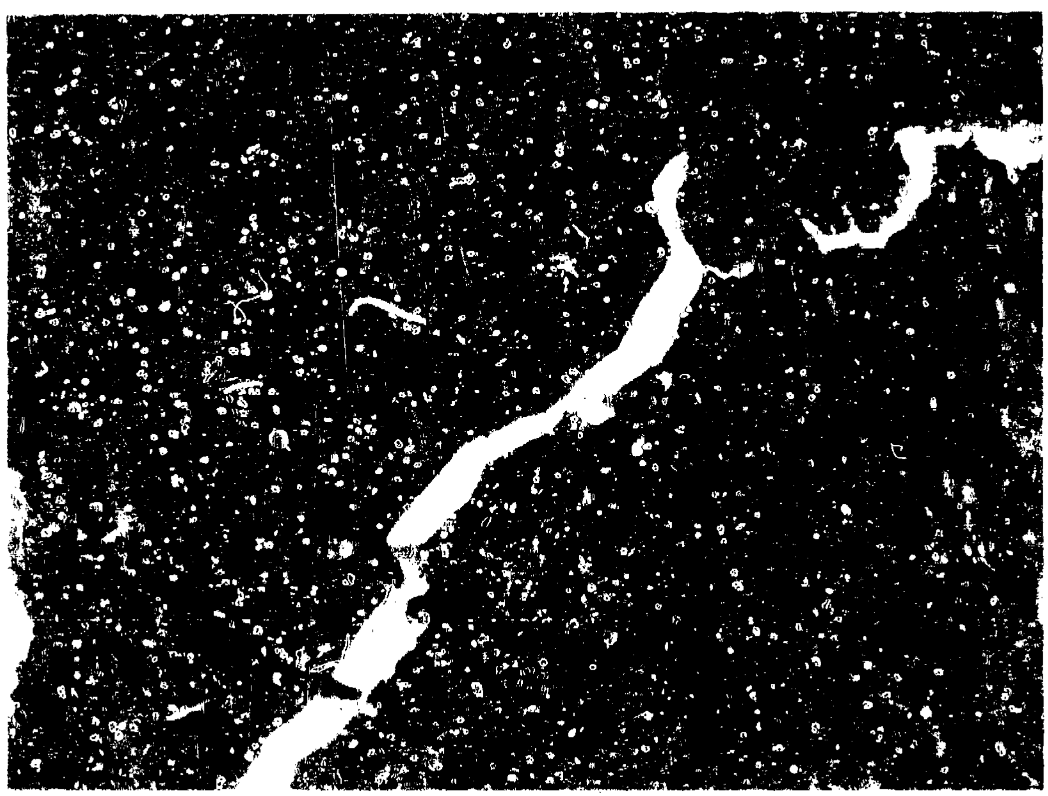


Electron Micrograph 15,000X

Figure 36. Microstructures of Udimet 500 specimen after test at 1500° F and 35,000 psi. Rupture life 441.6 hours.

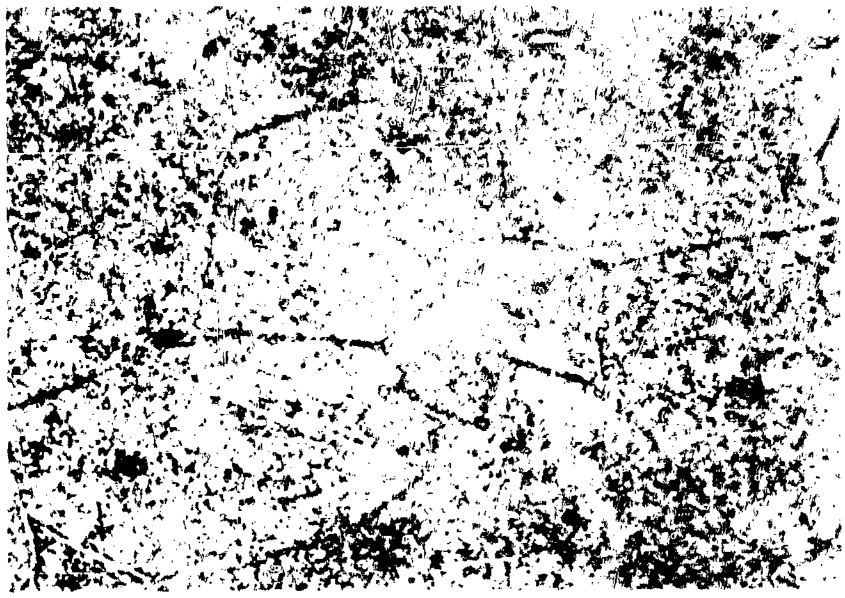


Photomicrograph 1000X

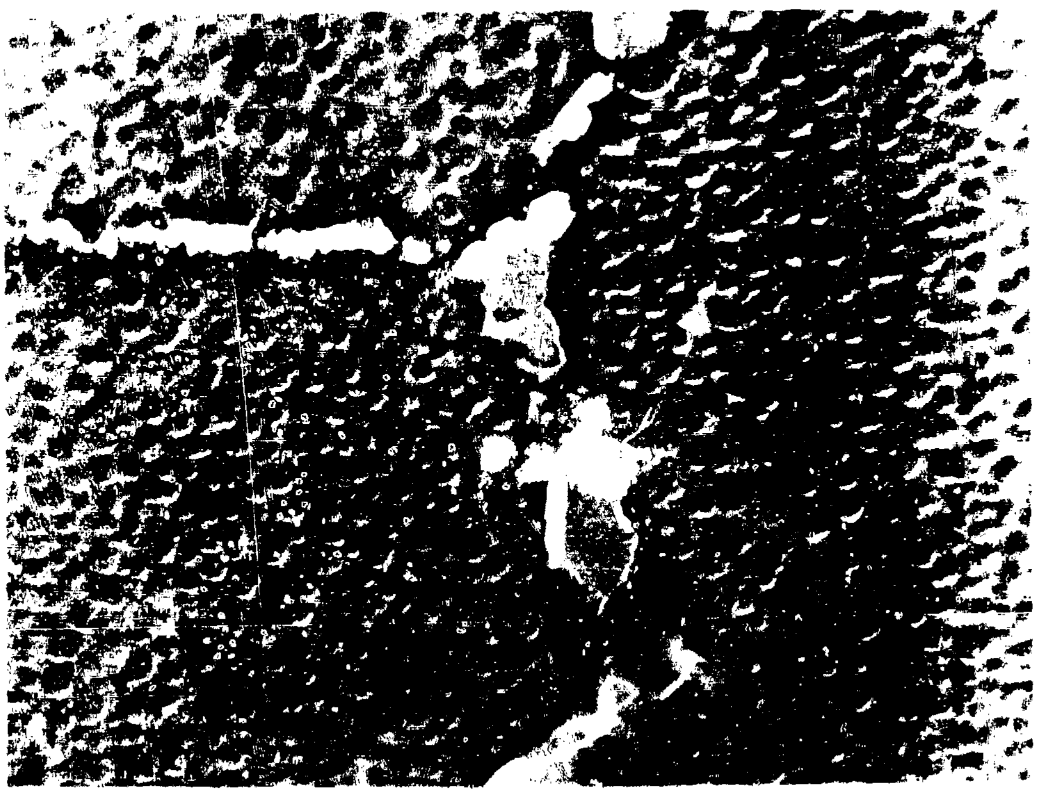


Electron Micrograph 15,000X

Figure 37. Microstructures of Udimet 500 specimen after test at 1500° F and 32,500 psi. Rupture life 548.8 hours.

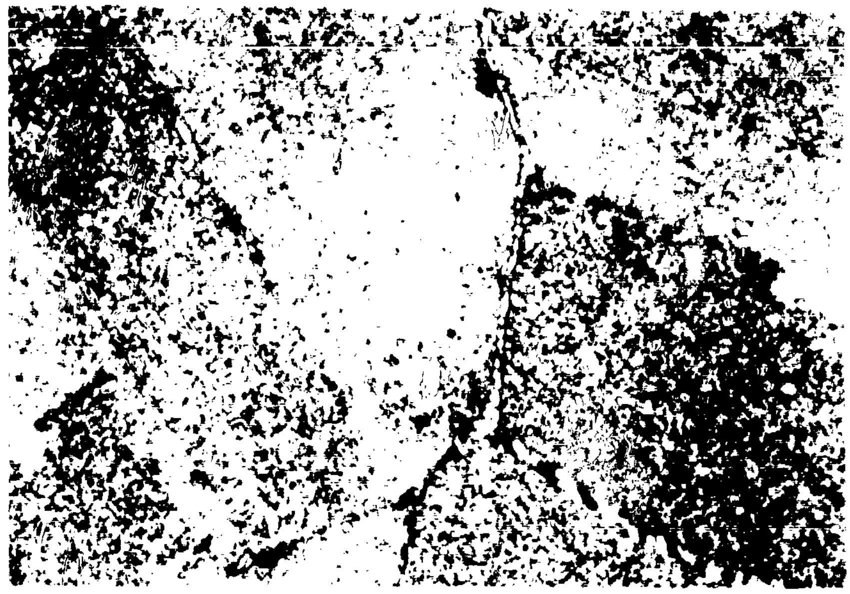


Photomicrograph 1000X

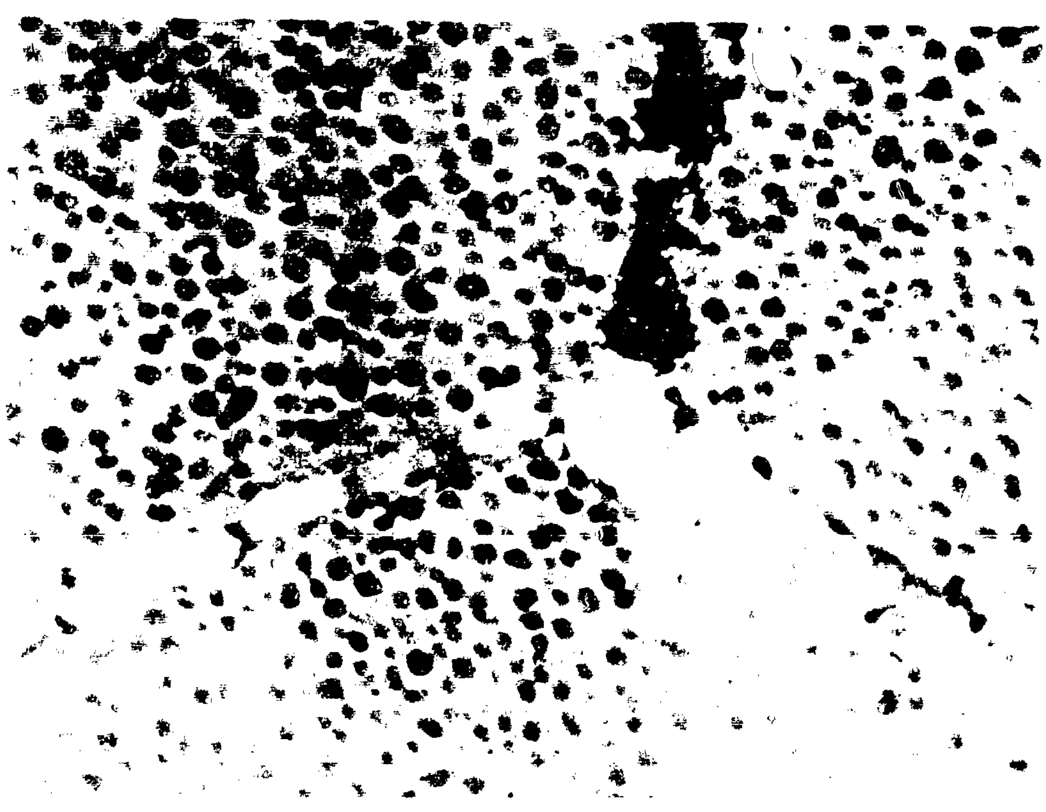


Electron Micrograph 15,000X

Figure 38. Microstructures of Udimet 500 specimen after test at 1500° F and 30,000 psi. Rupture life 1255.4 hours.

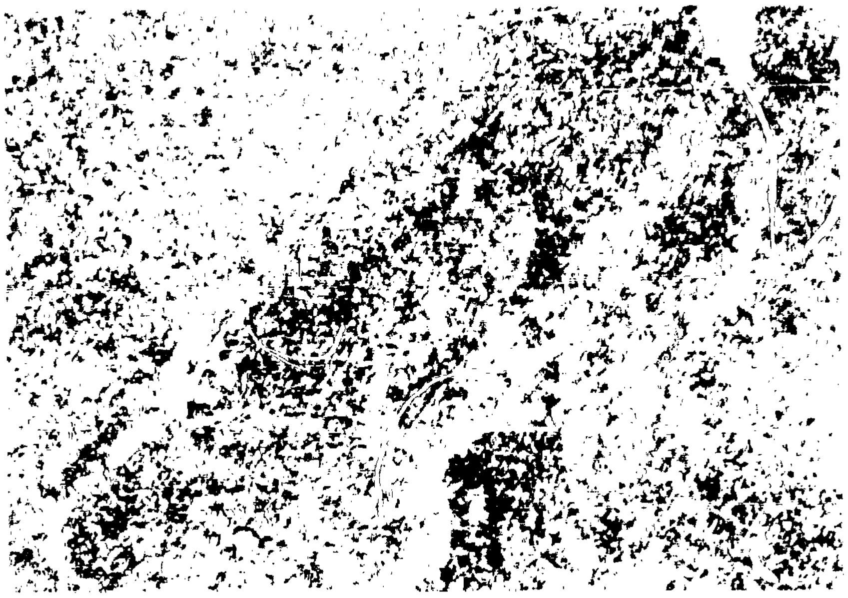


Photomicrograph 1000X

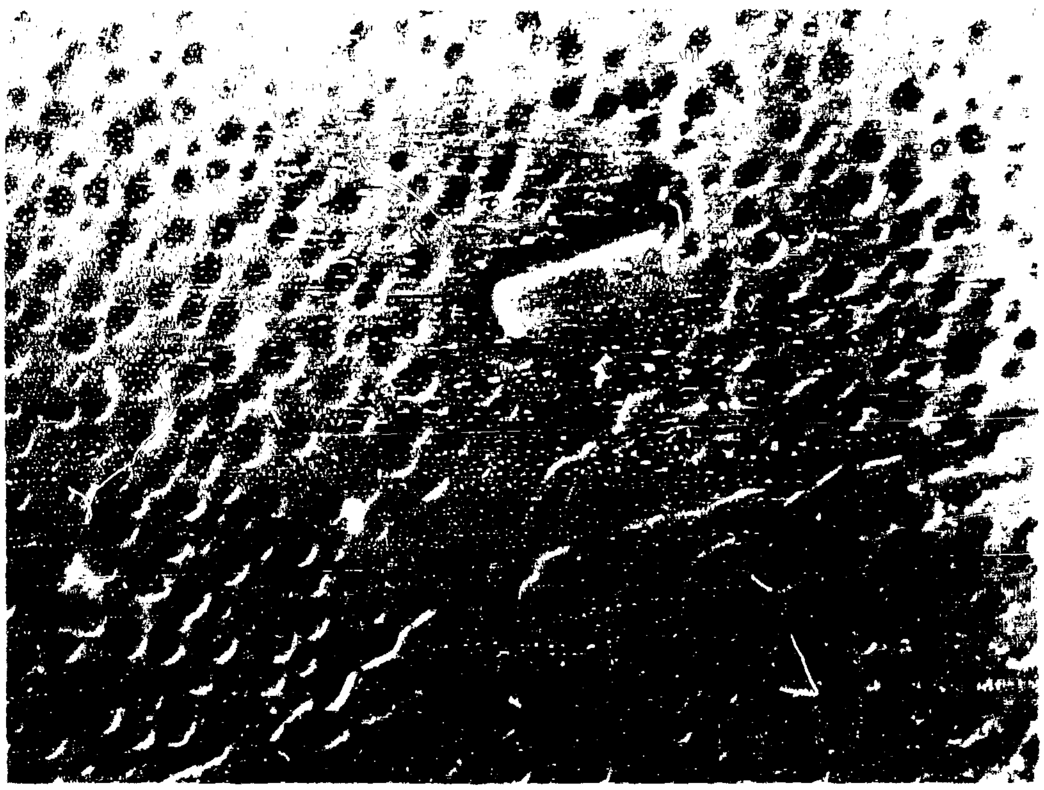


Electron Micrograph 15,000X

Figure 39. Microstructures of Udimet 500 specimen after test at 1500° F and 26,000 psi. Rupture life 2401.1 hours.



Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 40. Microstructures of Udimet 500 specimen after test at 1500° F and 23,000 psi. Rupture life 7146.6 hours.

Photomicrograph 1000X

Electron Micrograph 15,000X

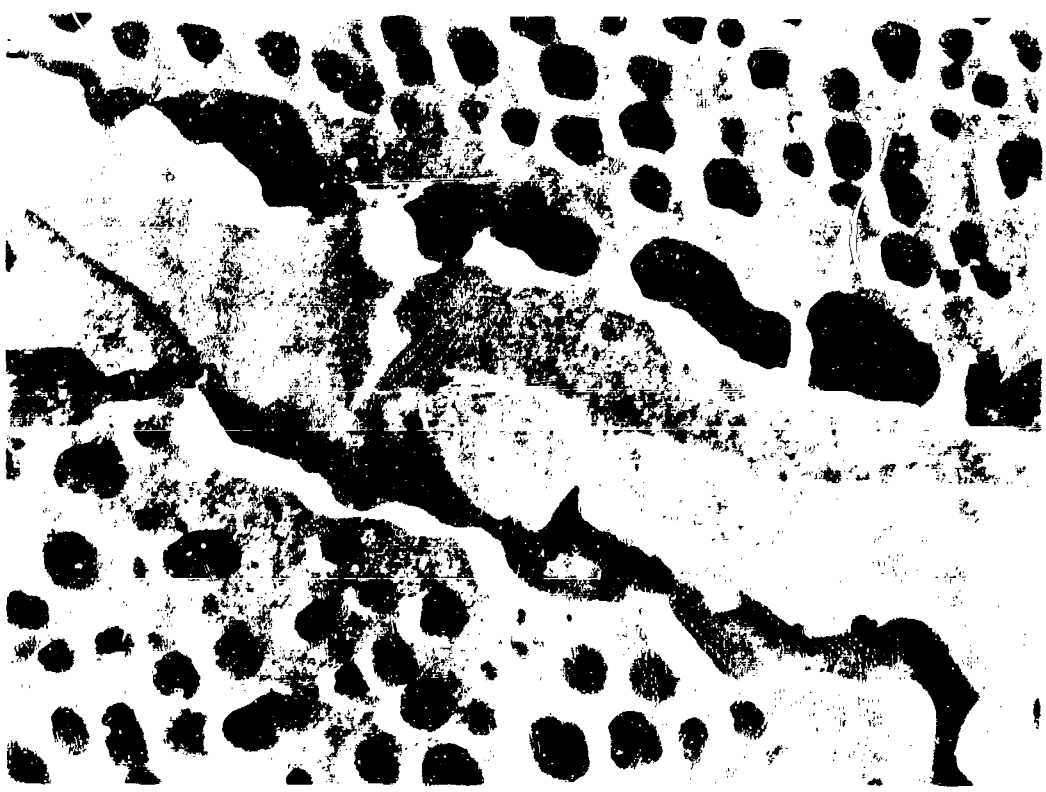
Figure 41. Microstructures of Udimet 500 specimen after test at 1500° F and 19,000 psi. Rupture life 14,773 hours.

Photomicrograph 1000X

Electron Micrograph 15,000X

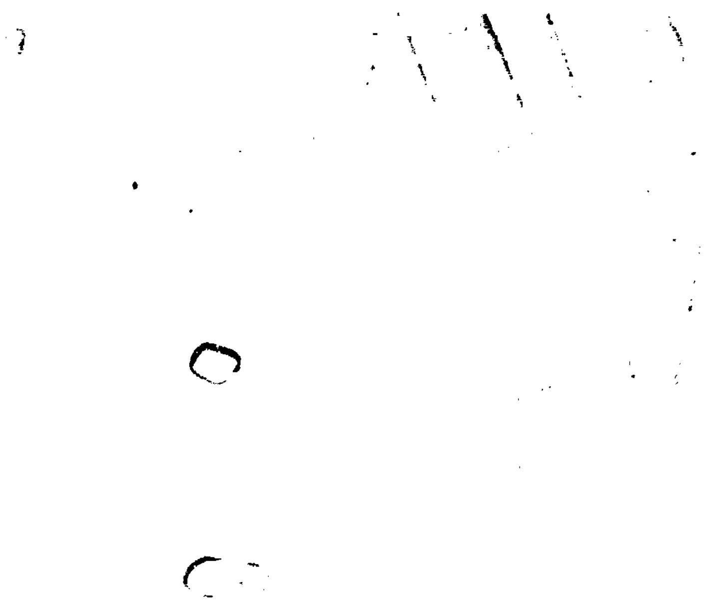
Figure 42. Microstructures of Udimet 500 specimen after test at 1500° F and 18,000 psi. Rupture life 12,880 hours.

Photomicrograph 1000X



Electron Micrograph 15,000X

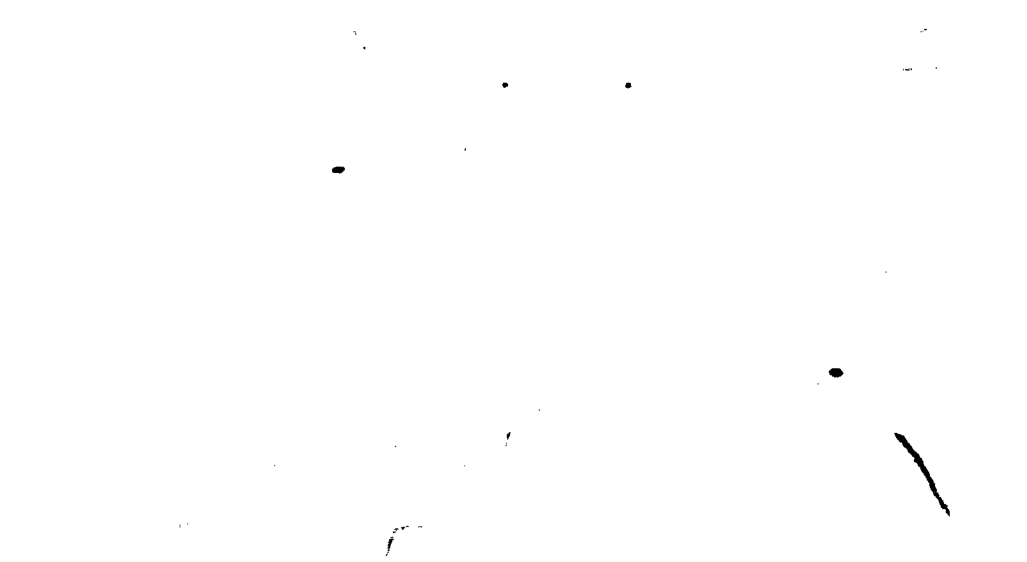
Figure 43. Microstructures of Udimet 500 specimen after test at 1500° F and 16,500 psi. Rupture life 24,733 hours.



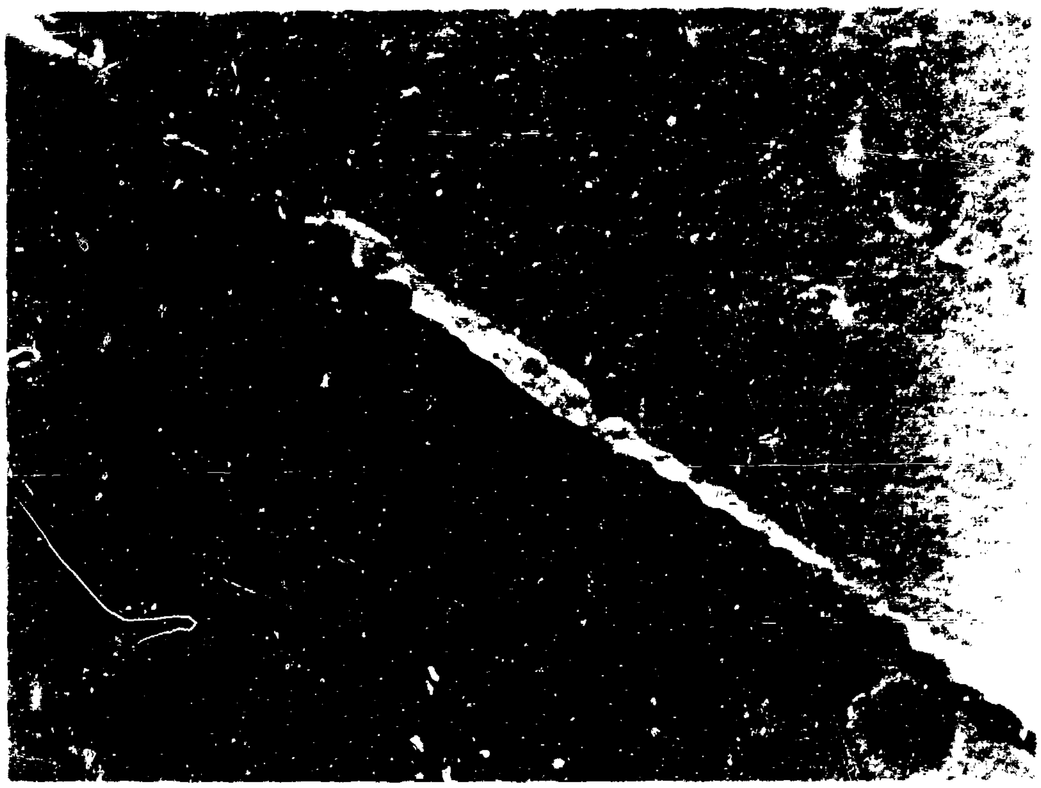
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 44. Microstructures of L-605. As received condition.



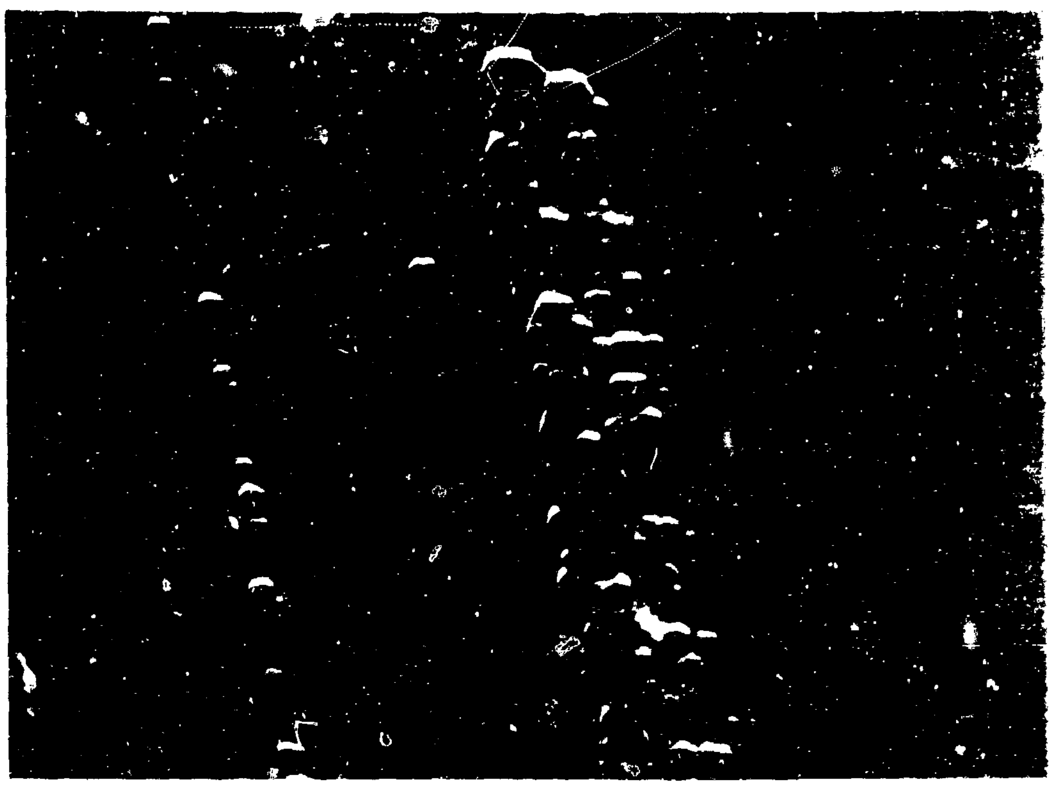
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 45. Microstructures of L-605 specimen after test at 1200° F and 65,000 psi. Rupture life 5.1 hours.

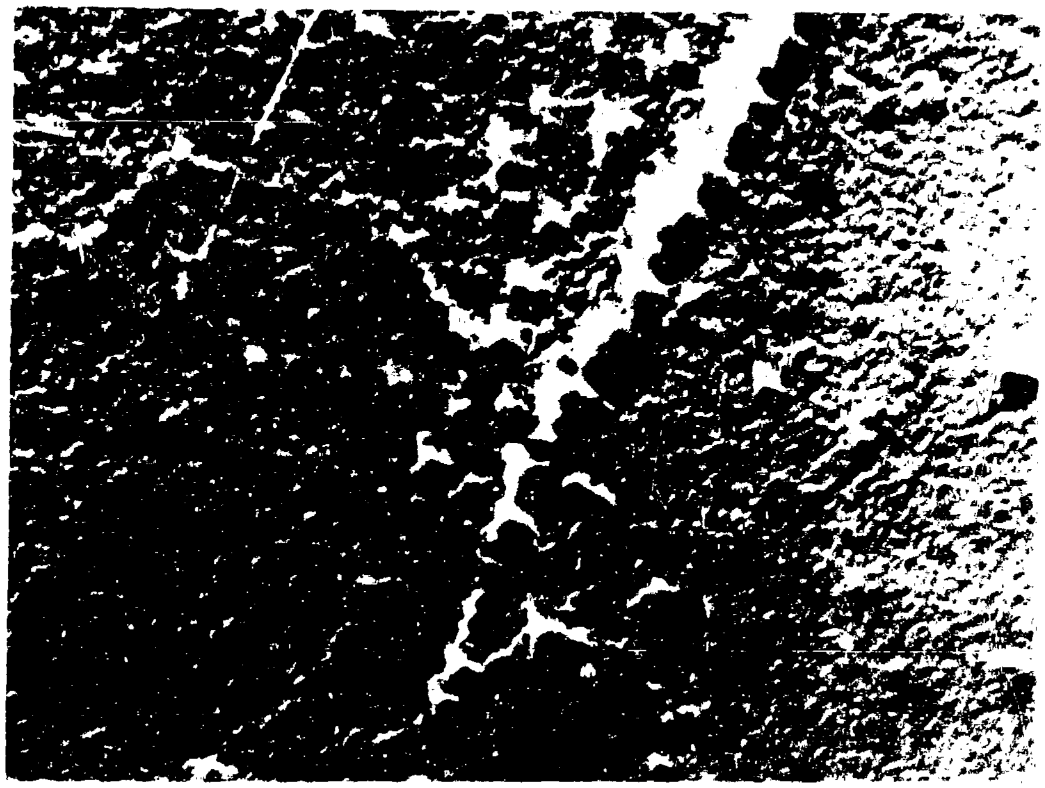
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 46. Microstructures of L-605 specimen after test at 1200° F and 62,500 psi. Rupture life 8.5 hours.

Photomicrograph 1000X



Electron Micrograph 15,000X

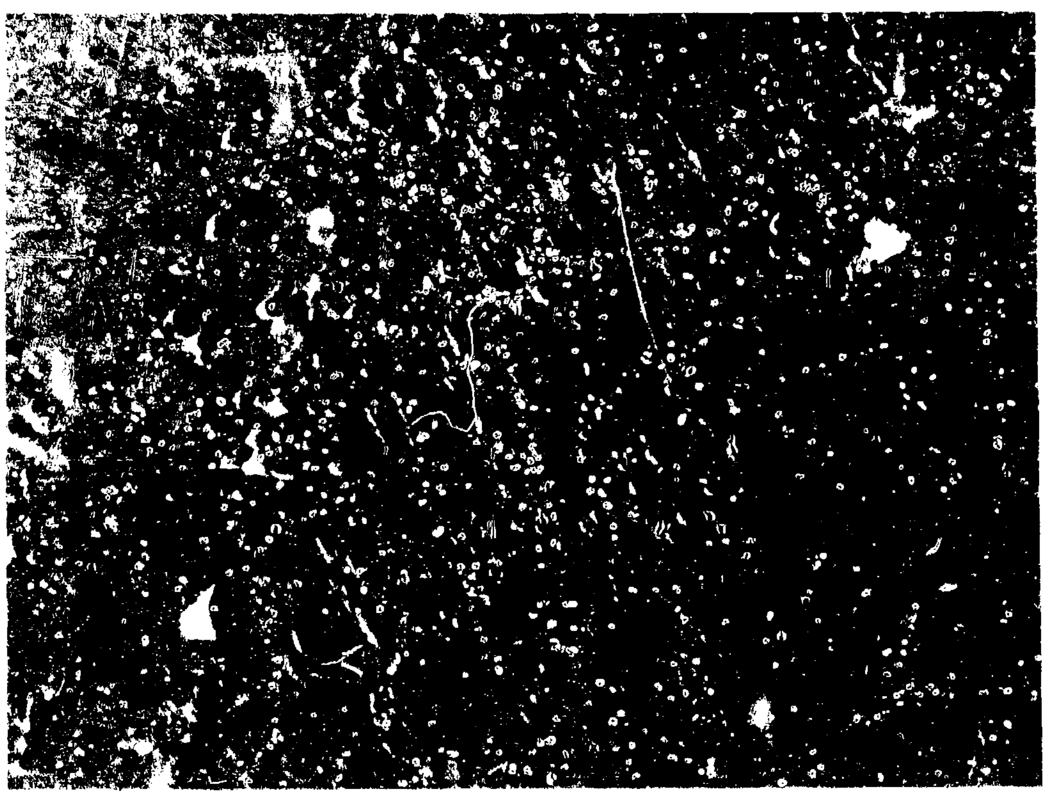
Figure 47. Microstructures of L-605 specimen after test at 1200° F and 58,000 psi. Rupture life 8.8 hours.

Photomicrograph 1000X

Electron Micrograph 15,000X

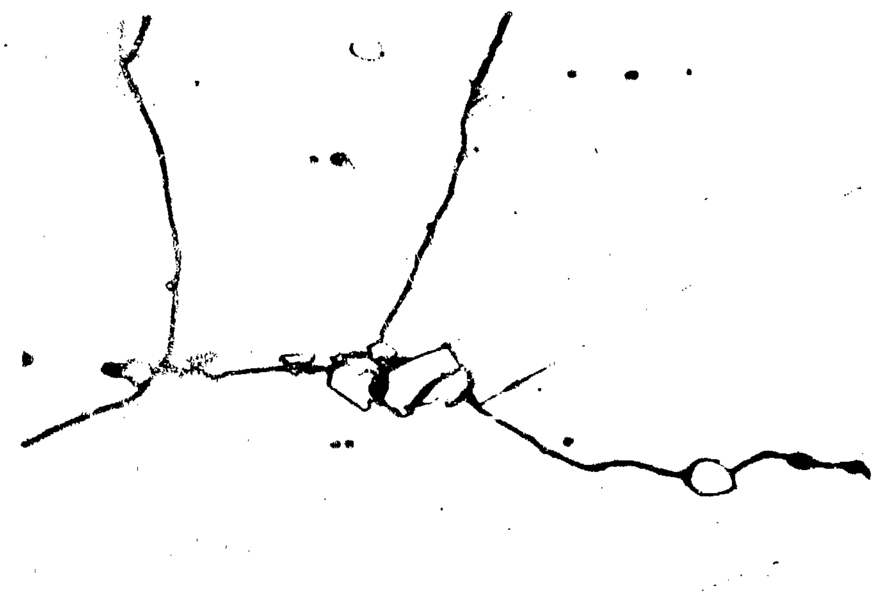
Figure 48. Microstructures of L-605 specimen after test at 1200° F and 54,000 psi. Rupture life 23.1 hours.

Photomicrograph 1000X

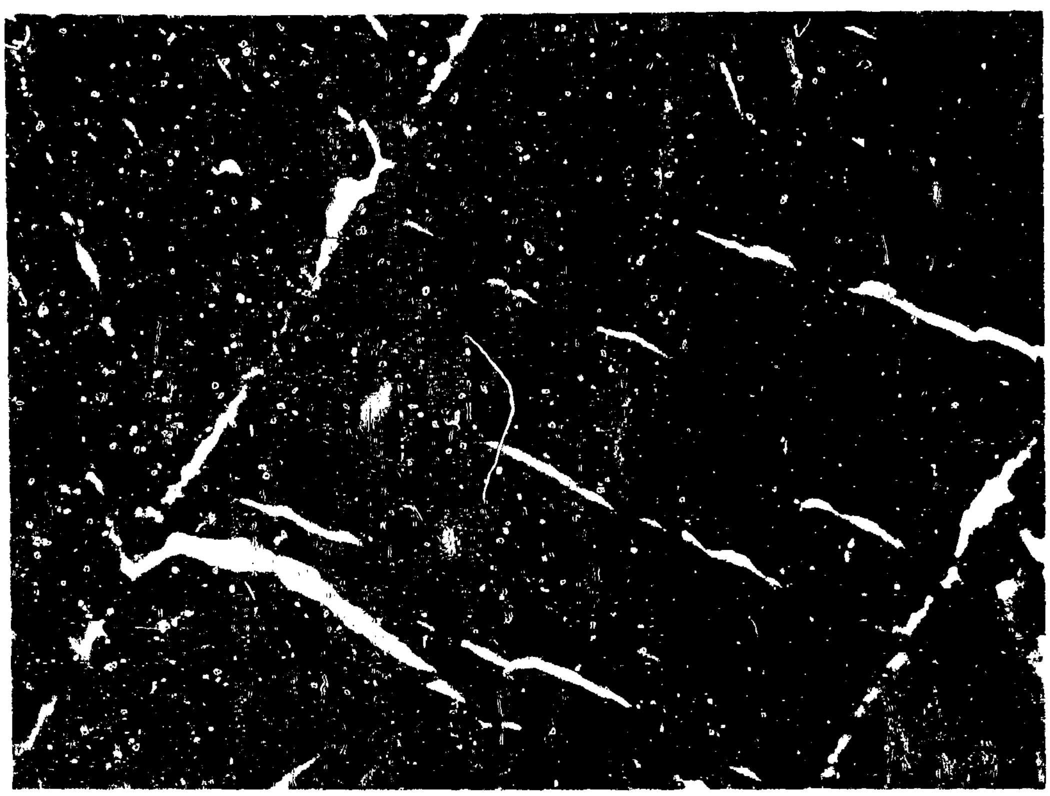


Electron Micrograph 15,000X

Figure 49. Microstructures of L-605 specimen after test at 1200° F and 51,000 psi. Rupture life 64.4 hours.



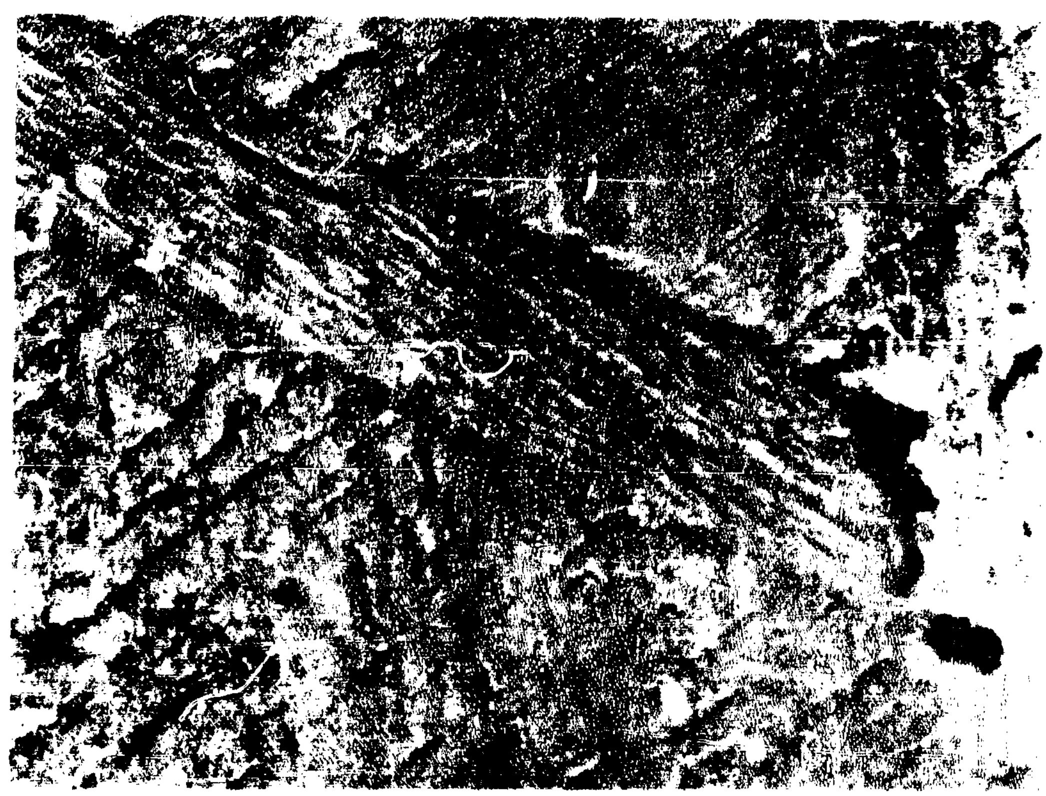
Photomicrograph 1000X



Electron Micrograph 15,000X

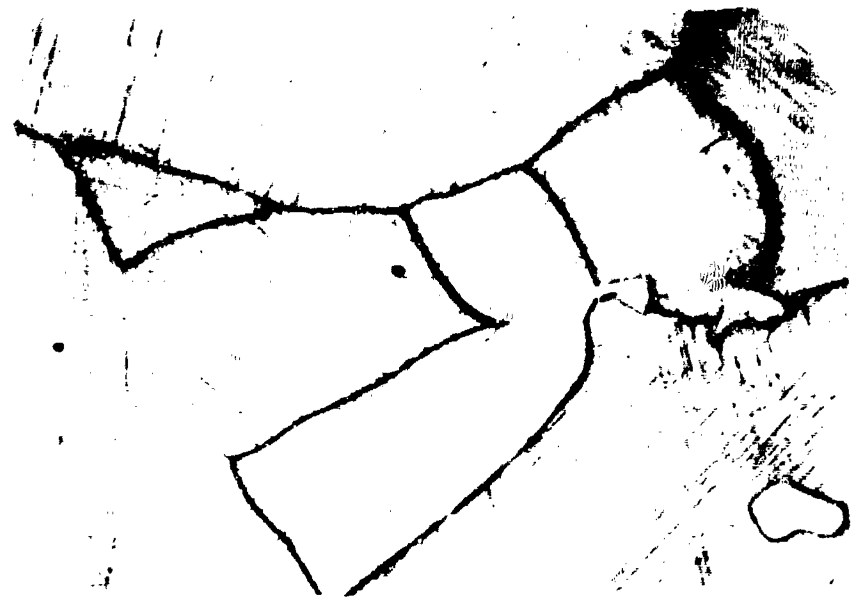
Figure 50. Microstructures of L-605 specimen after test at 1200° F and 50,000 psi. Rupture life 51.6 hours.

Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 51. Microstructures of L-605 specimen after test at 1200° F and 45,000 psi. Rupture life 136.9 hours.



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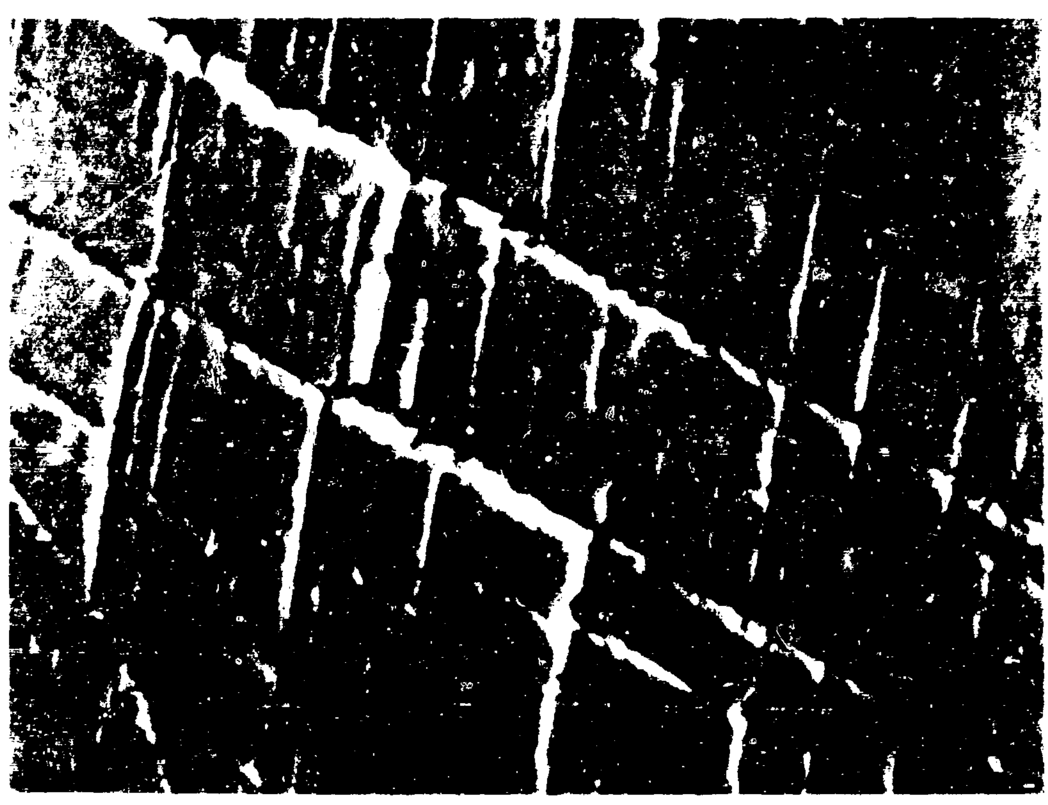
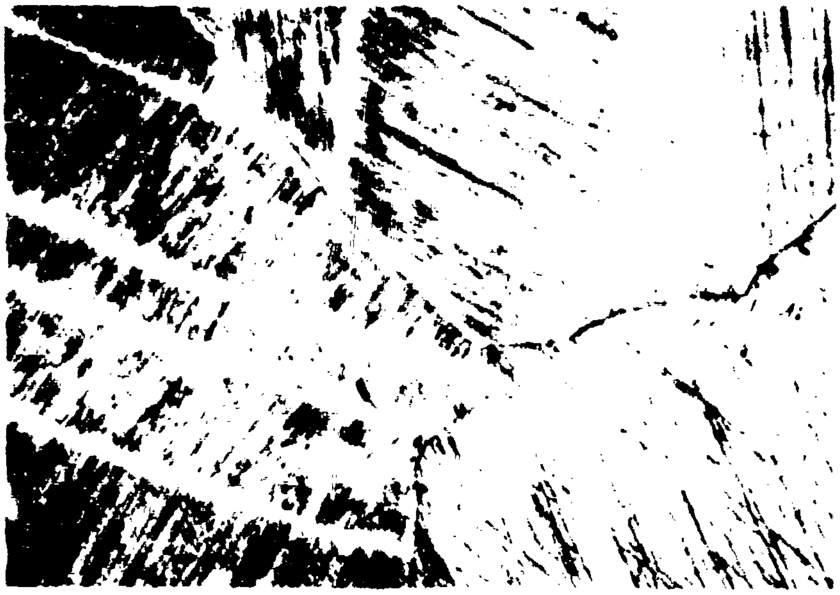
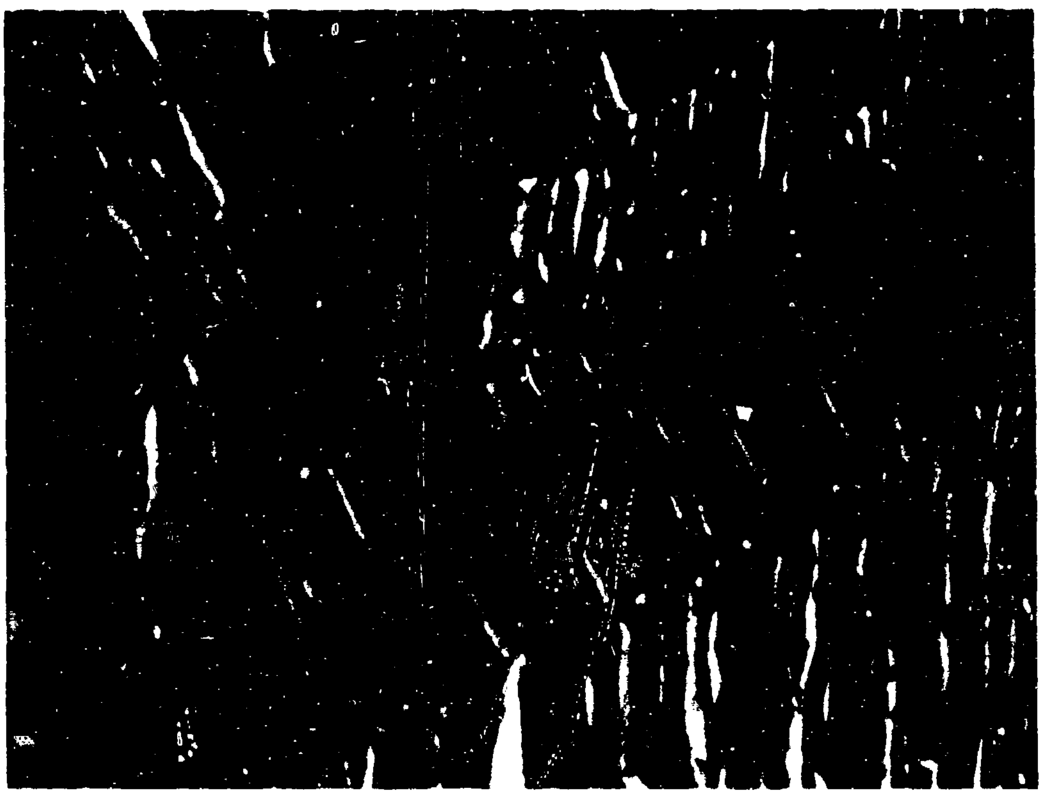


Electron Micrograph 15,000X

Figure 52. Microstructures of L-605 specimen after test at 1200° F and 42,500 psi. Rupture life 20[illegible].1 hours.



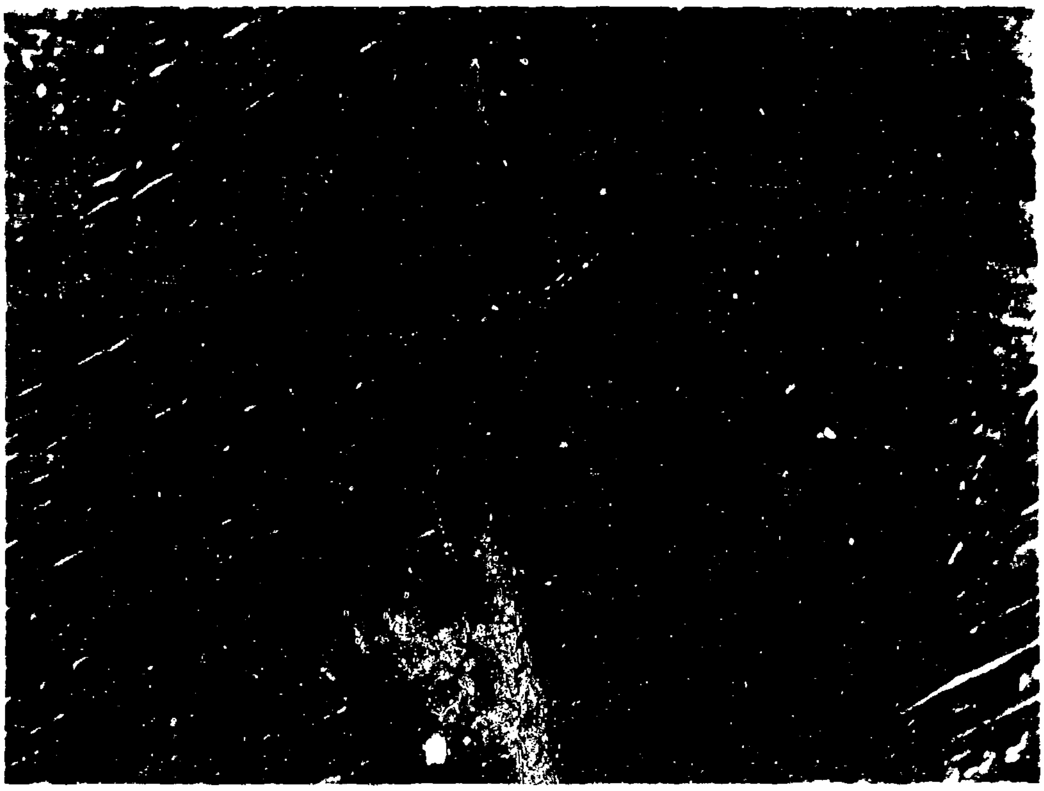
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 53. Microstructures of L-605 specimen after test at 1200° F and 41,000 psi. Rupture life 822.8 hours.

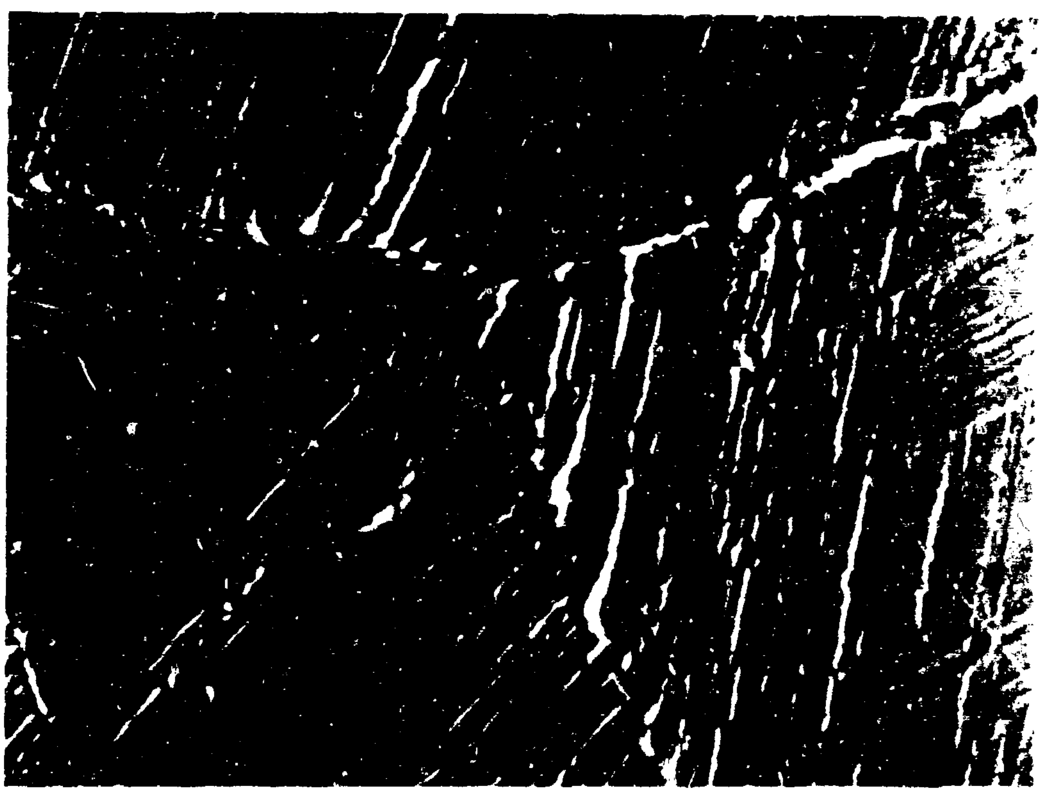
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 54. Microstructures of L-605 specimen after test at 1200° F and 37,500 psi. Rupture life 1693.6 hours.

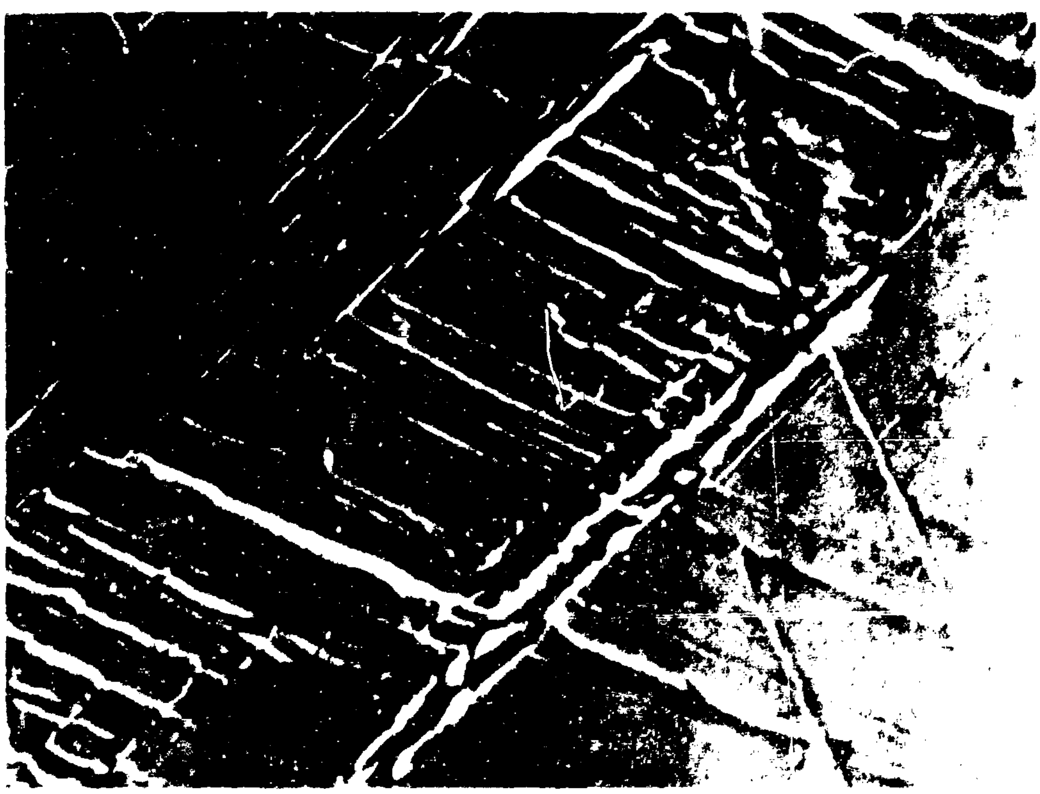
Photomicrograph 1000X



Electron Micrograph 15,000X

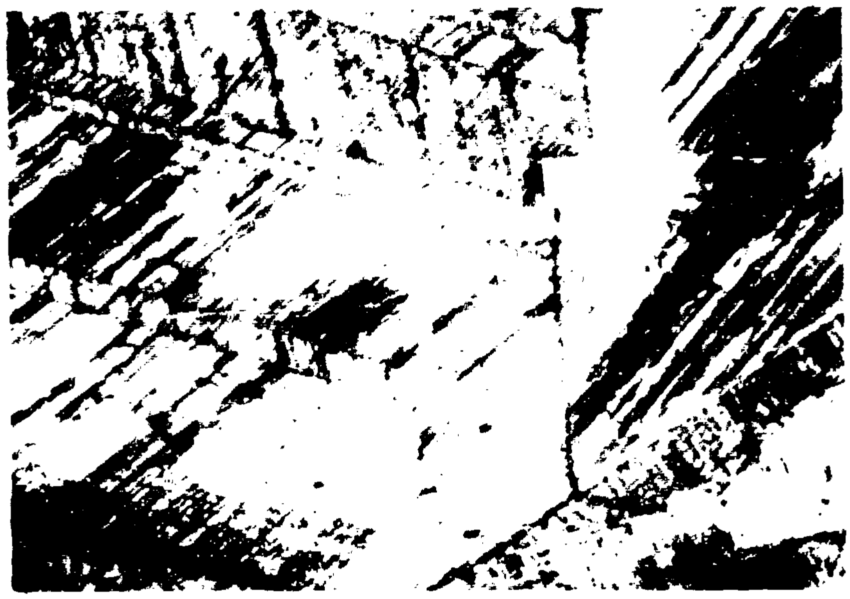
Figure 55. Microstructures of L-605 specimen after test at 1200° F and 35,000 psi. Rupture life 3445.5 hours.

Photomicrograph 1000X

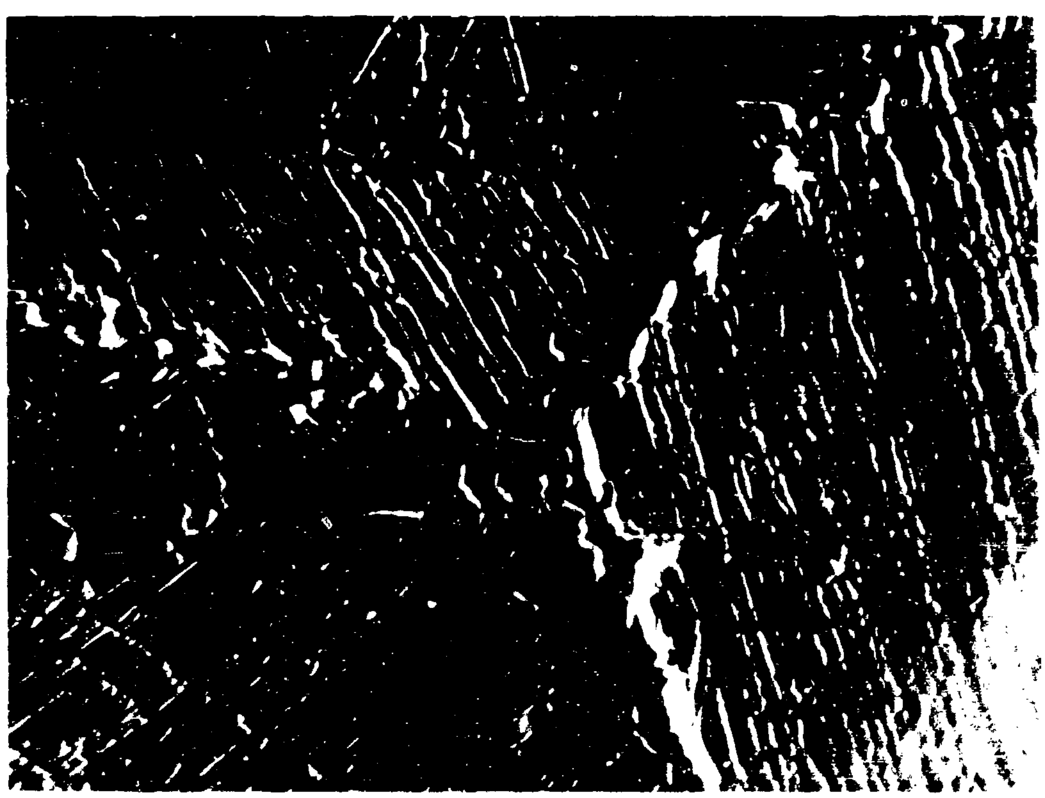


Electron Micrograph 15,000X

Figure 56. Microstructures of L-605 specimen after test at 1200° F and 31,000 psi. Rupture life 3294.0 hours.



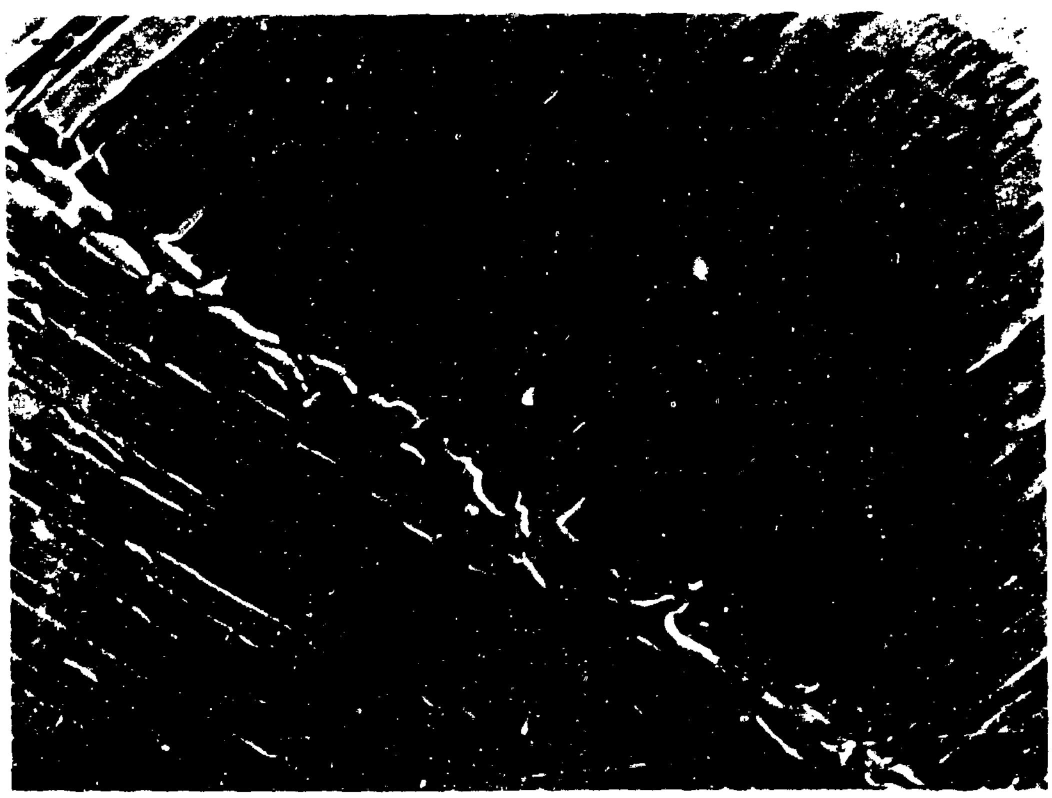
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 57. Microstructures of L-605 specimen after test at 1200° F and 29,500 psi. Rupture life 21,720 hours.

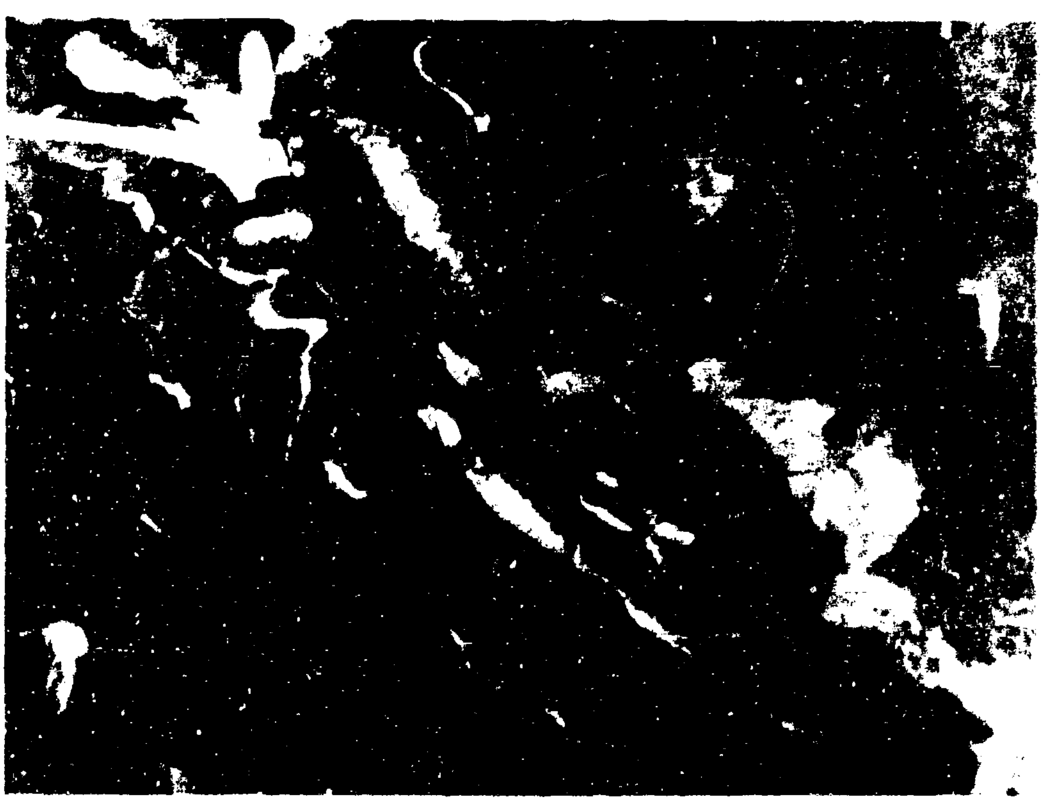
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 58. Microstructures of L-605 specimen after test at 1200° F and 28,000 psi. Rupture life 10,192 hours.

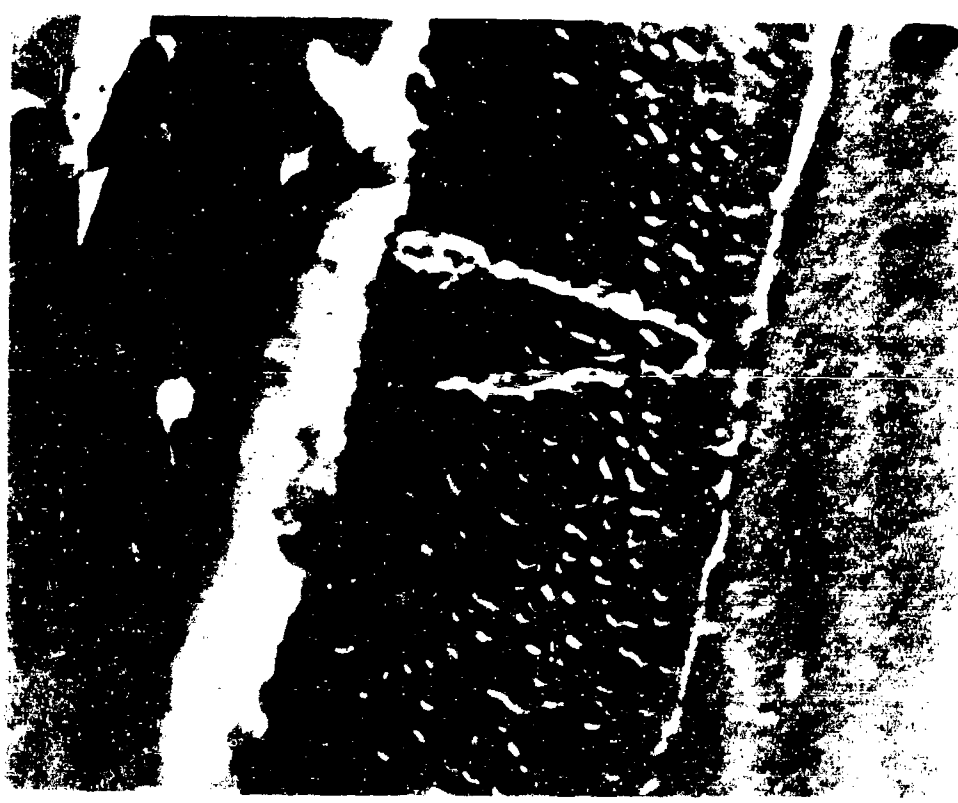
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 59. Microstructures of L-605 specimen after test at 1500° F and 37,500 psi. Rupture life 1.7 hours.

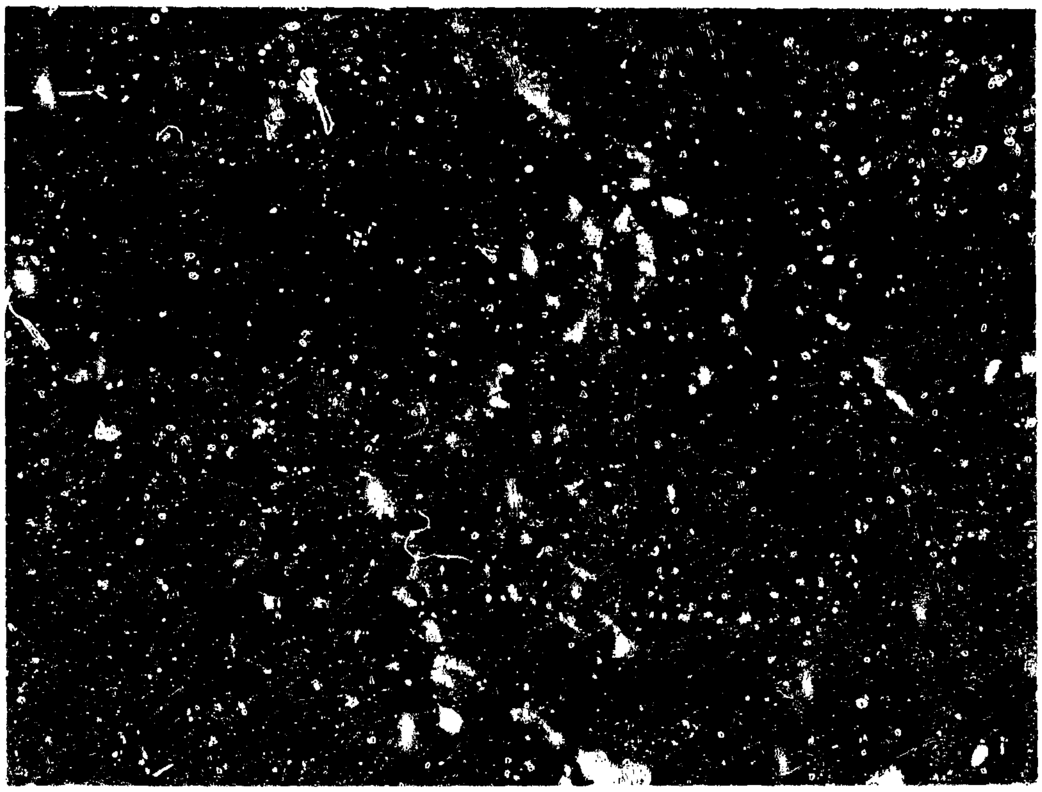
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 60. Microstructures of L-605 specimen after test at 1500° F and 35,000 psi. Rupture life 2.7 hours.

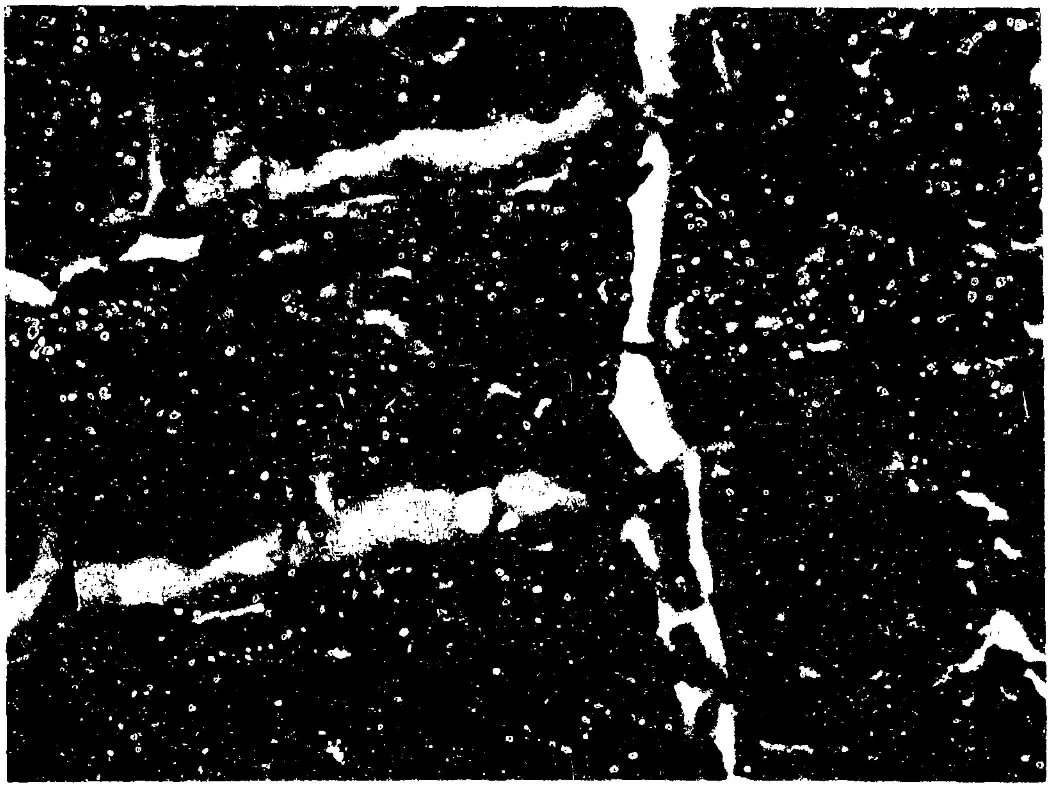
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 61. Microstructures of L-605 specimen after test at 1500° F and 30,000 psi. Rupture life 13.8 hours.

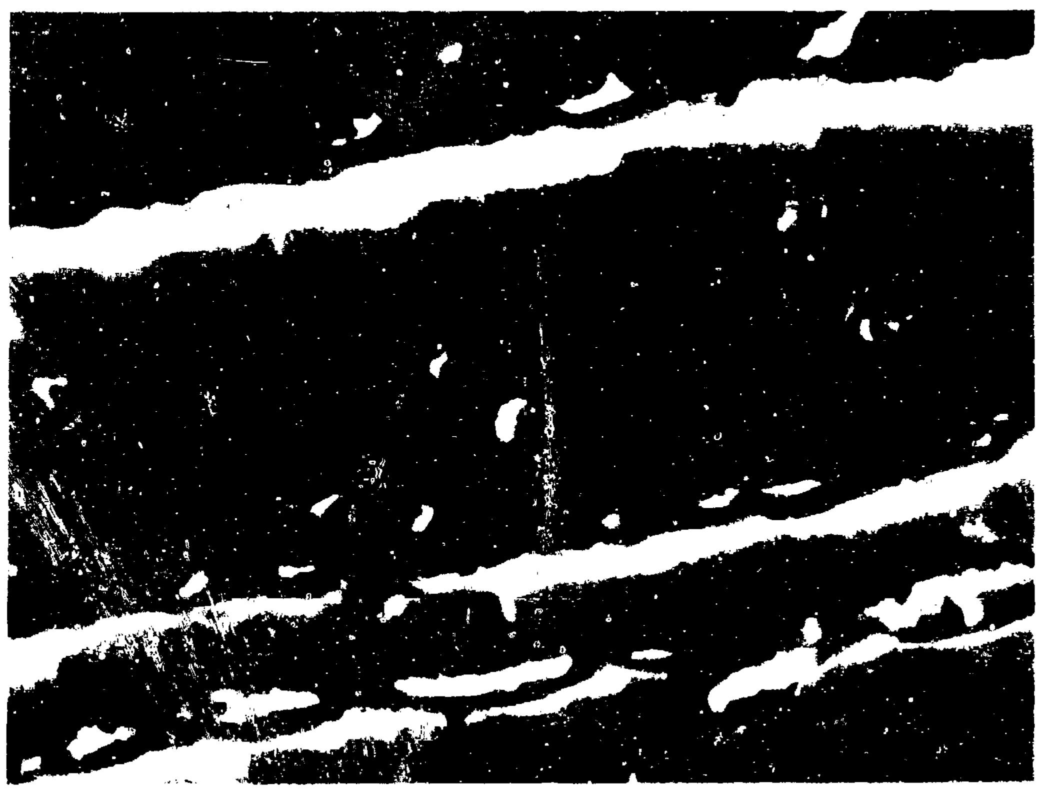
Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 62. Microstructures of L-605 specimen after test at 1500° F and 27,500 psi. Rupture life 25.7 hours.

Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 63. Microstructures of L-605 specimen after test at 1500° F and 25,000 psi. Rupture life 96.5 hours.

Photomicrograph 1000X

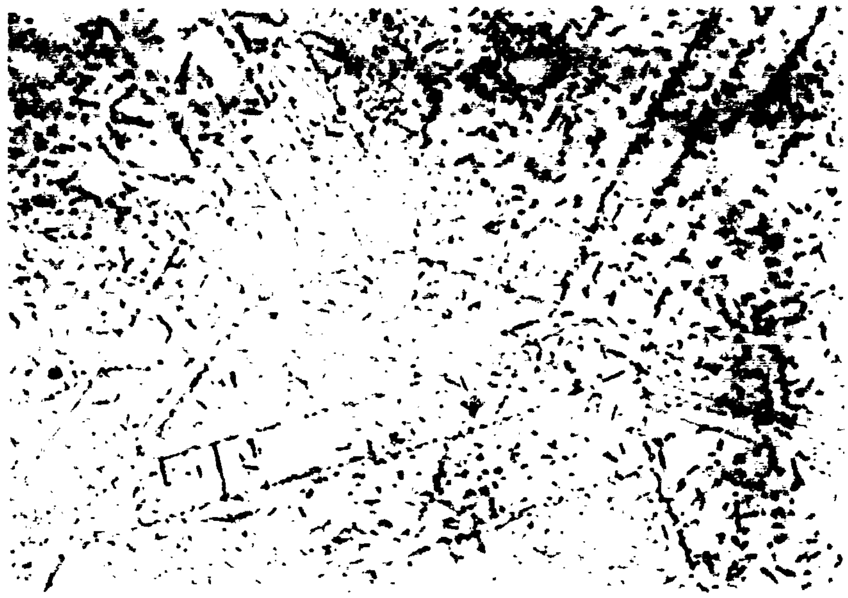
Electron Micrograph 15,000X

Figure 64. Microstructures of L-605 specimen after test at 1500° F and 22,000 psi. Rupture life 146.0 hours.

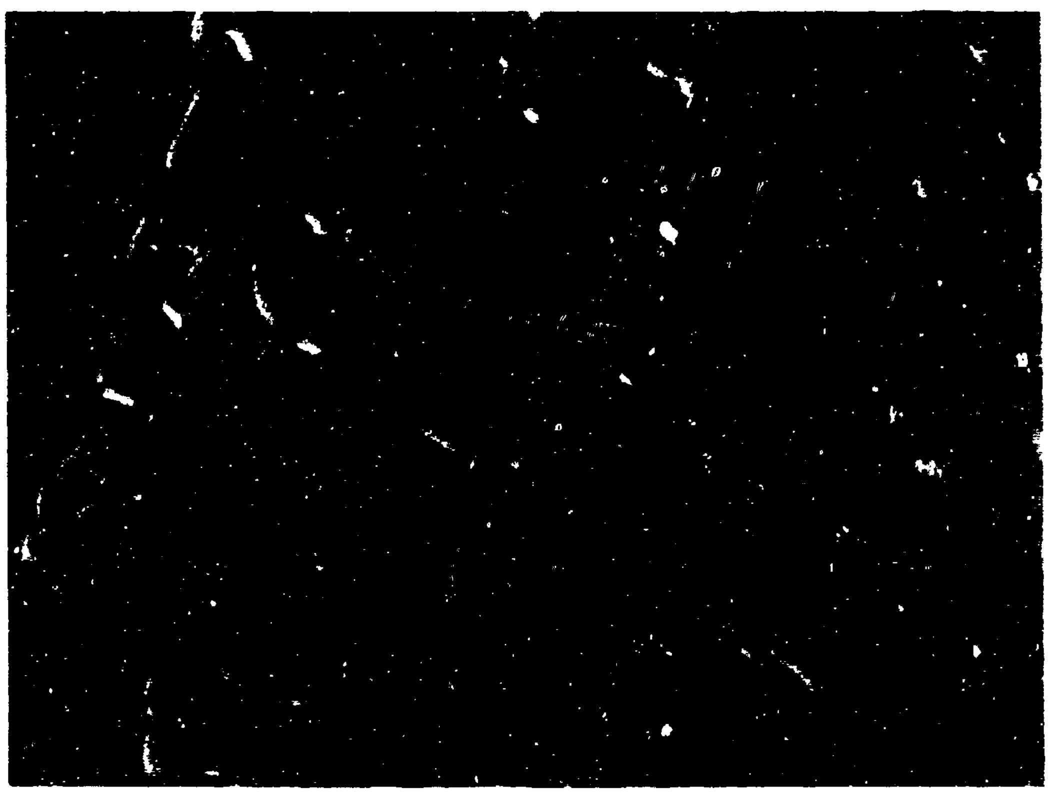
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 65. Microstructures of L-605 specimen after test at 1500° F and 21,500 psi. Rupture life 301.0 hours.

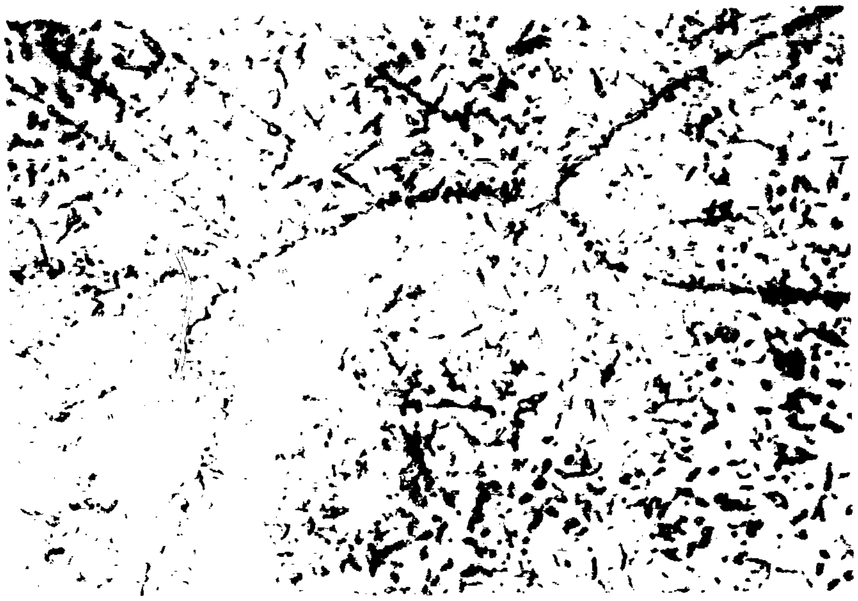


Photomicrograph 1000X



Electron Micrograph 15,000X

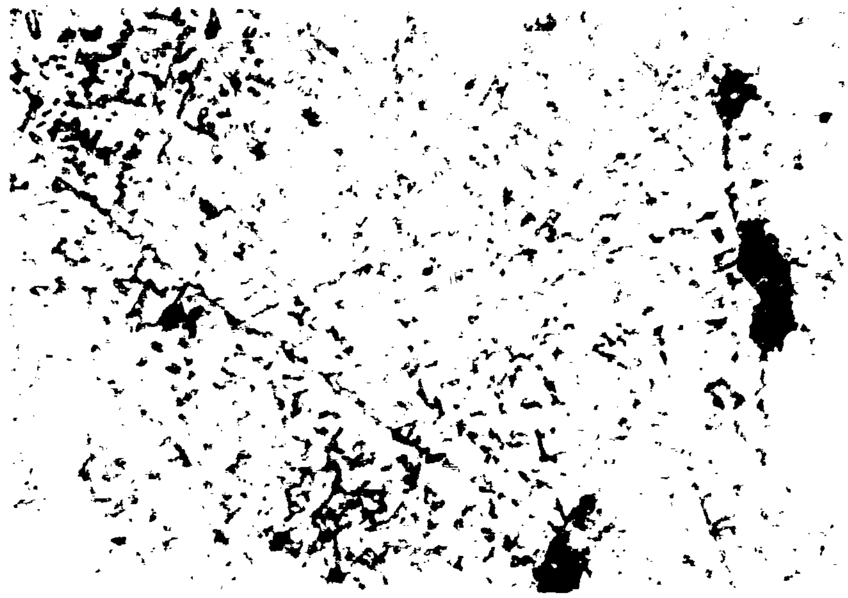
Figure 66. Microstructures of L-605 specimen after test at 1500° F and 18,500 psi. Rupture life 748.3 hours.



Photomicrograph 1000X

Electron Micrograph 15,000X

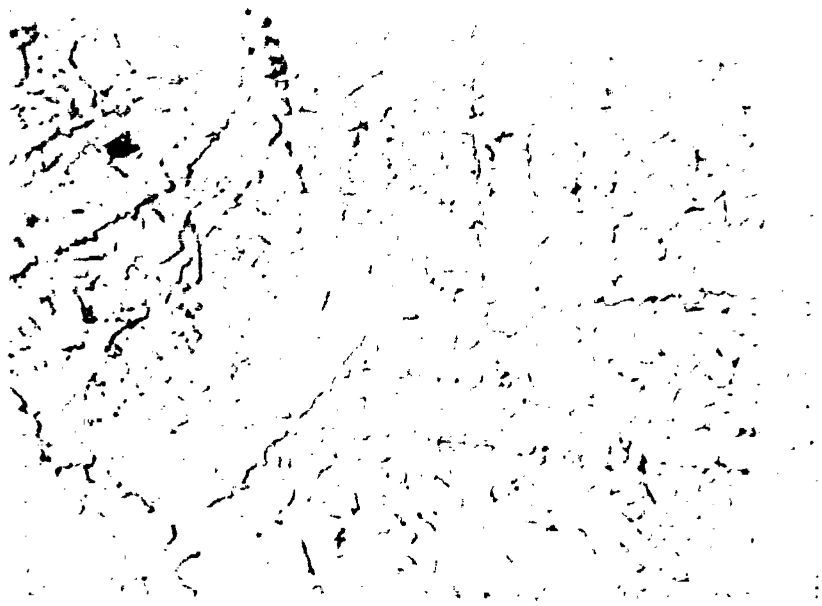
Figure 67. Microstructures of L-605 specimen after test at 1500° F and 15,000 psi. Rupture life 3883.8 hours.



Photomicrograph 1000X

Electron Micrograph 15,000X

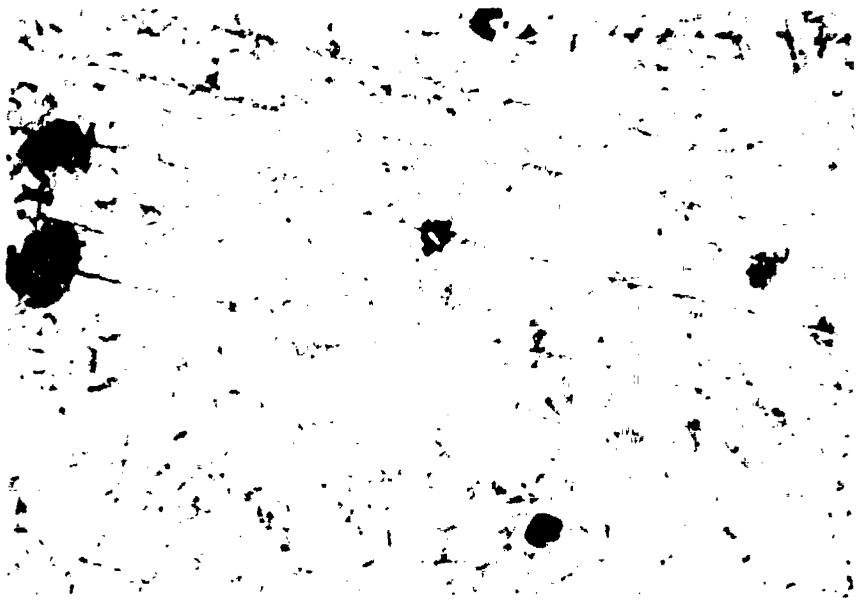
Figure 68. Microstructures of L-605 specimen after test at 1500° F and 13,000 psi. Rupture life 11,077.5 hours.



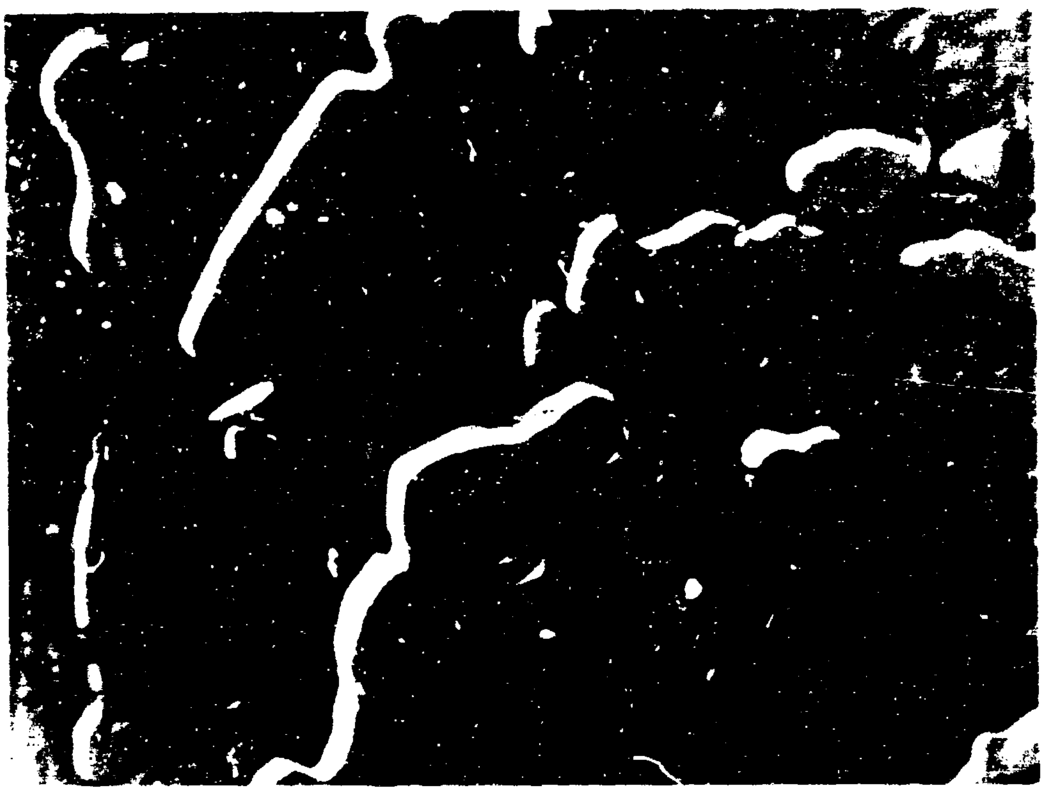
Photomicrograph 1000X

Electron Micrograph 15,000X

Figure 69. Microstructures of L-605 specimen after test at 1500° F and 11,500 psi. Rupture life 13,018 hours.



Photomicrograph 1000X



Electron Micrograph 15,000X

Figure 70. Microstructures of L-605 specimen after test at 1500° F and 10,500 psi. Rupture life 34,600 hours.

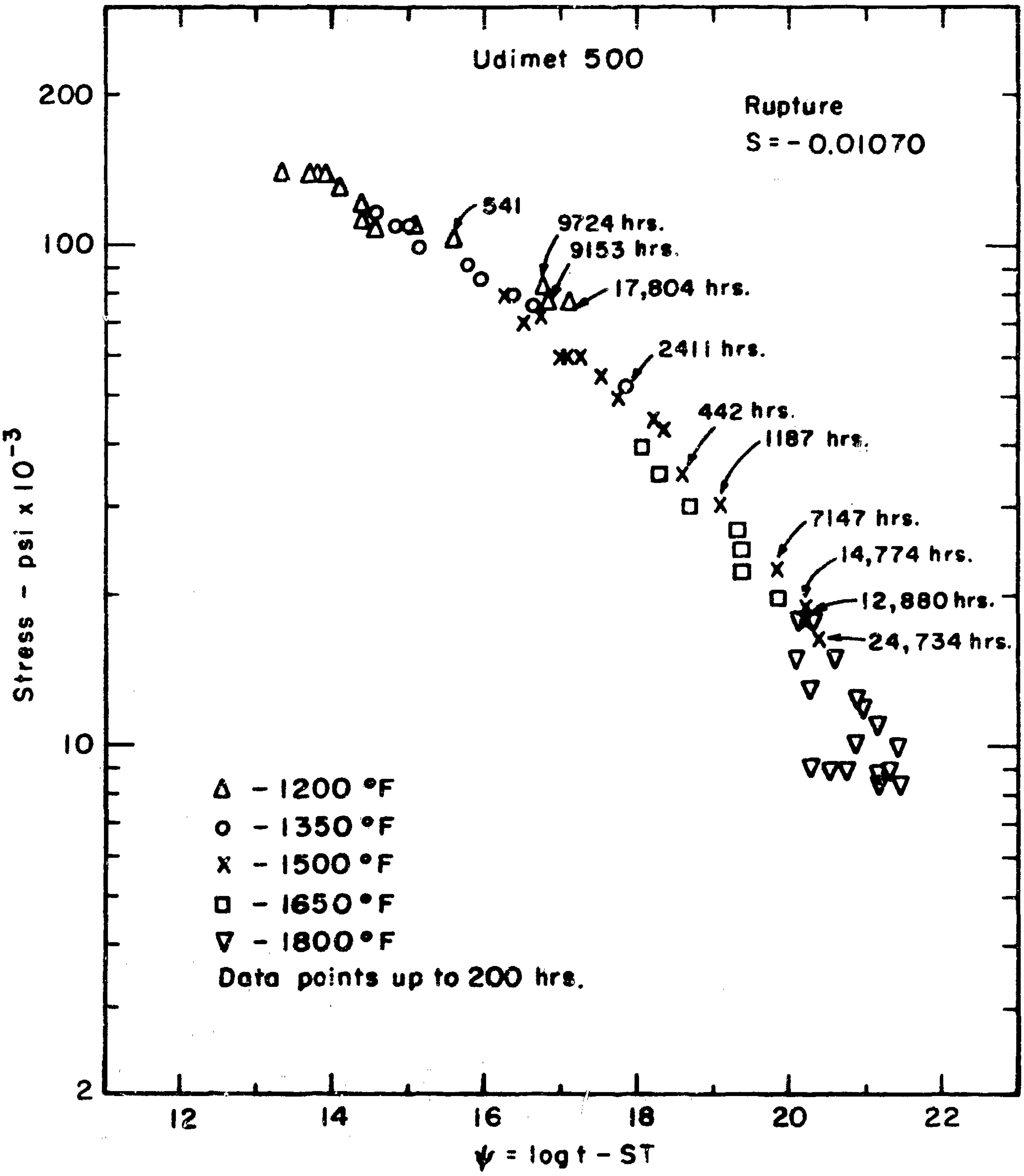


Figure 71: Manson-Haferd plot, Udimet 500, rupture.

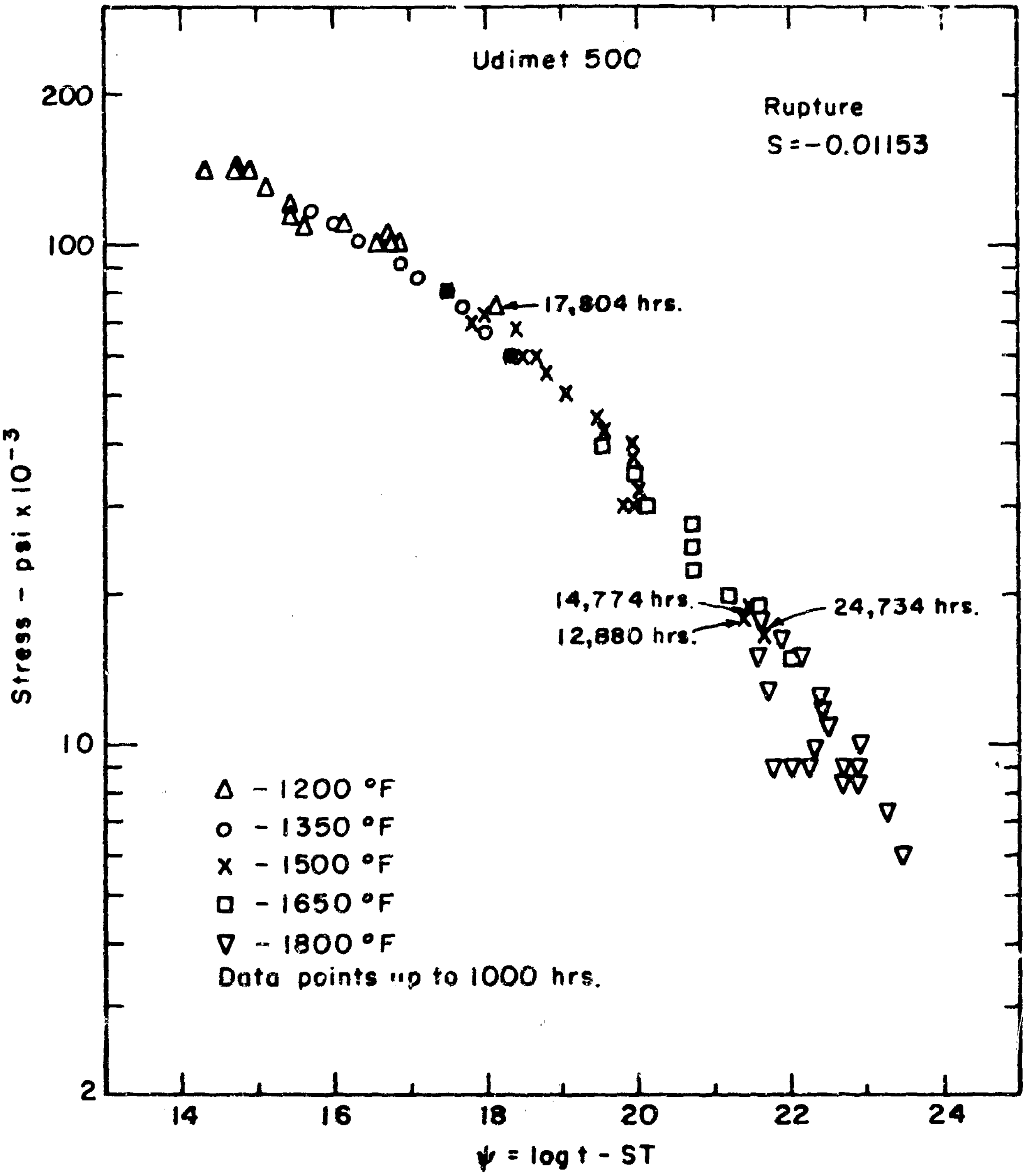


Figure 72: Manson-Haford plot, Udimet 500, rupture.

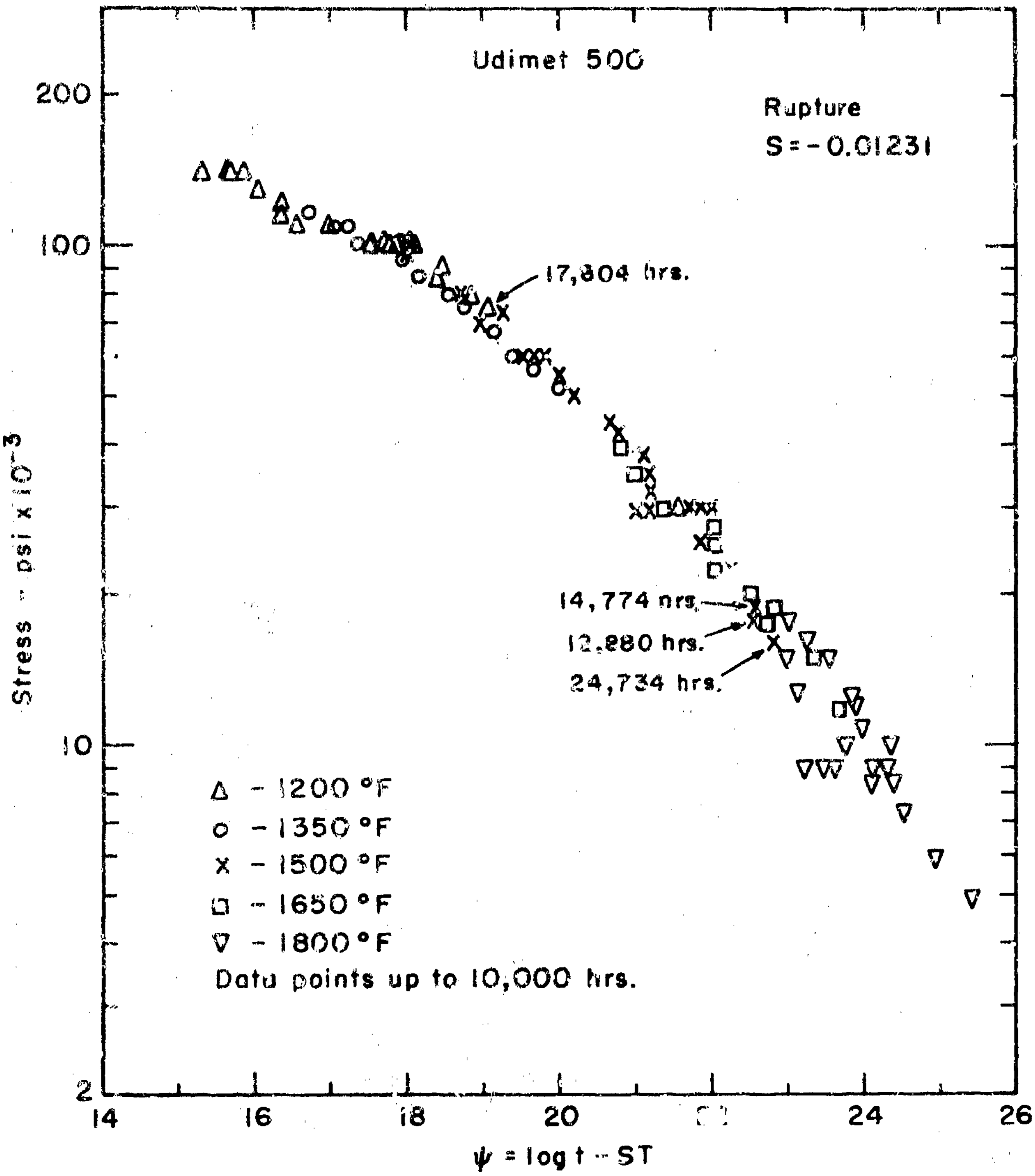


Figure 73: Manson–Haford plot, Udimet 500, rupture.

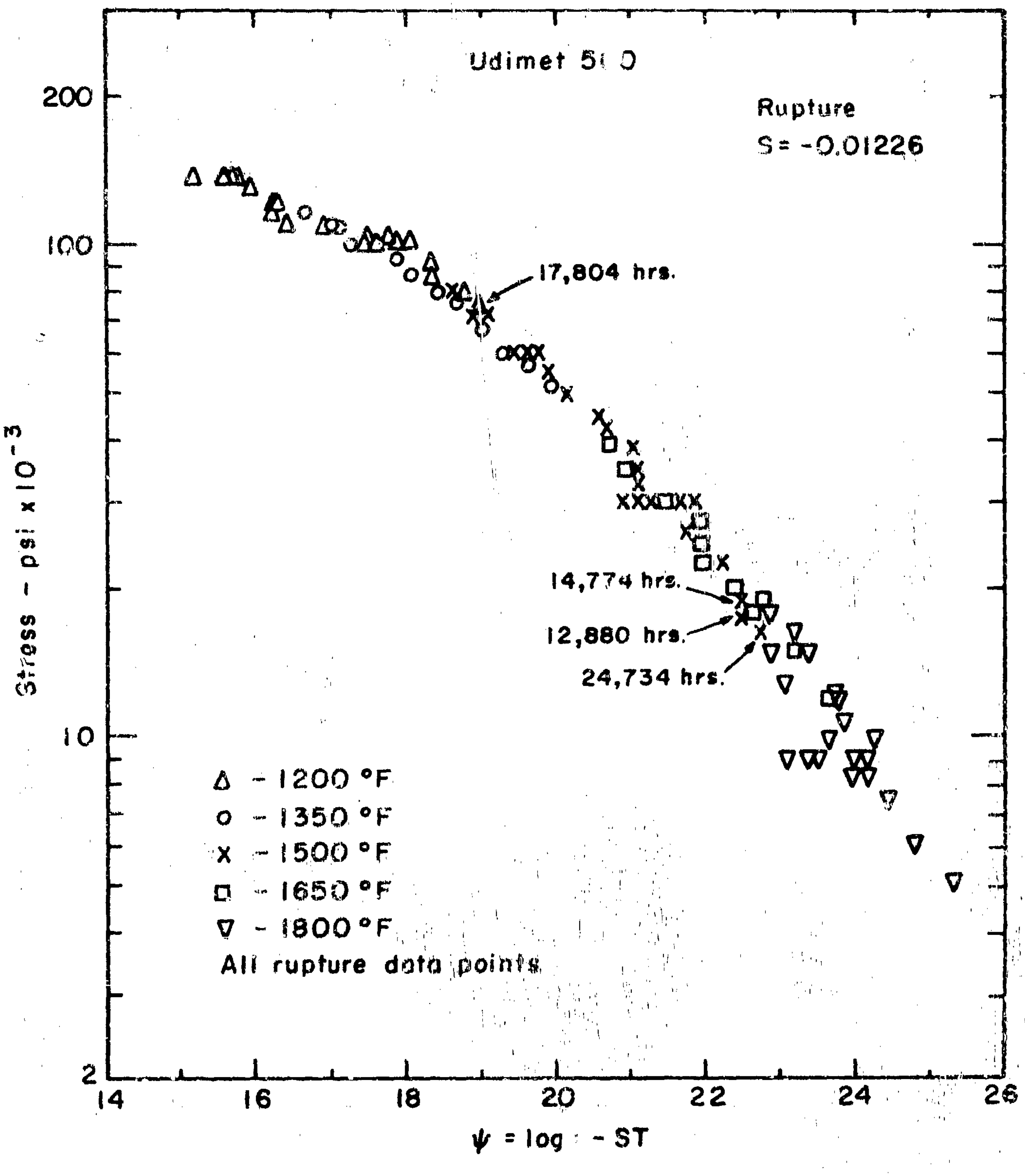


Figure 74: Manson—Haford plot, Udimet 500, rupture

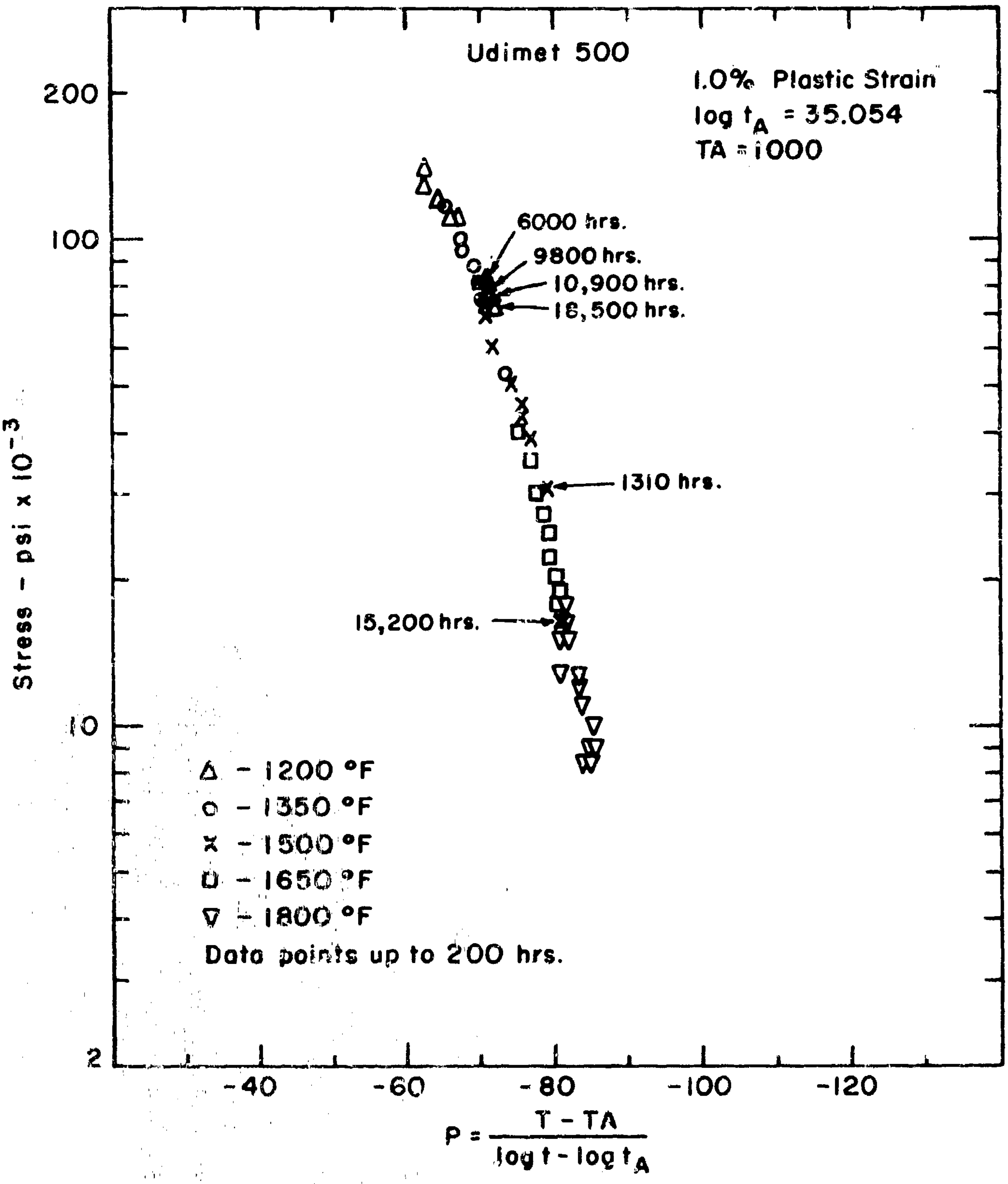


Figure 75: Manson—Haford plot, Udimet 500, 1.0% plastic strain.

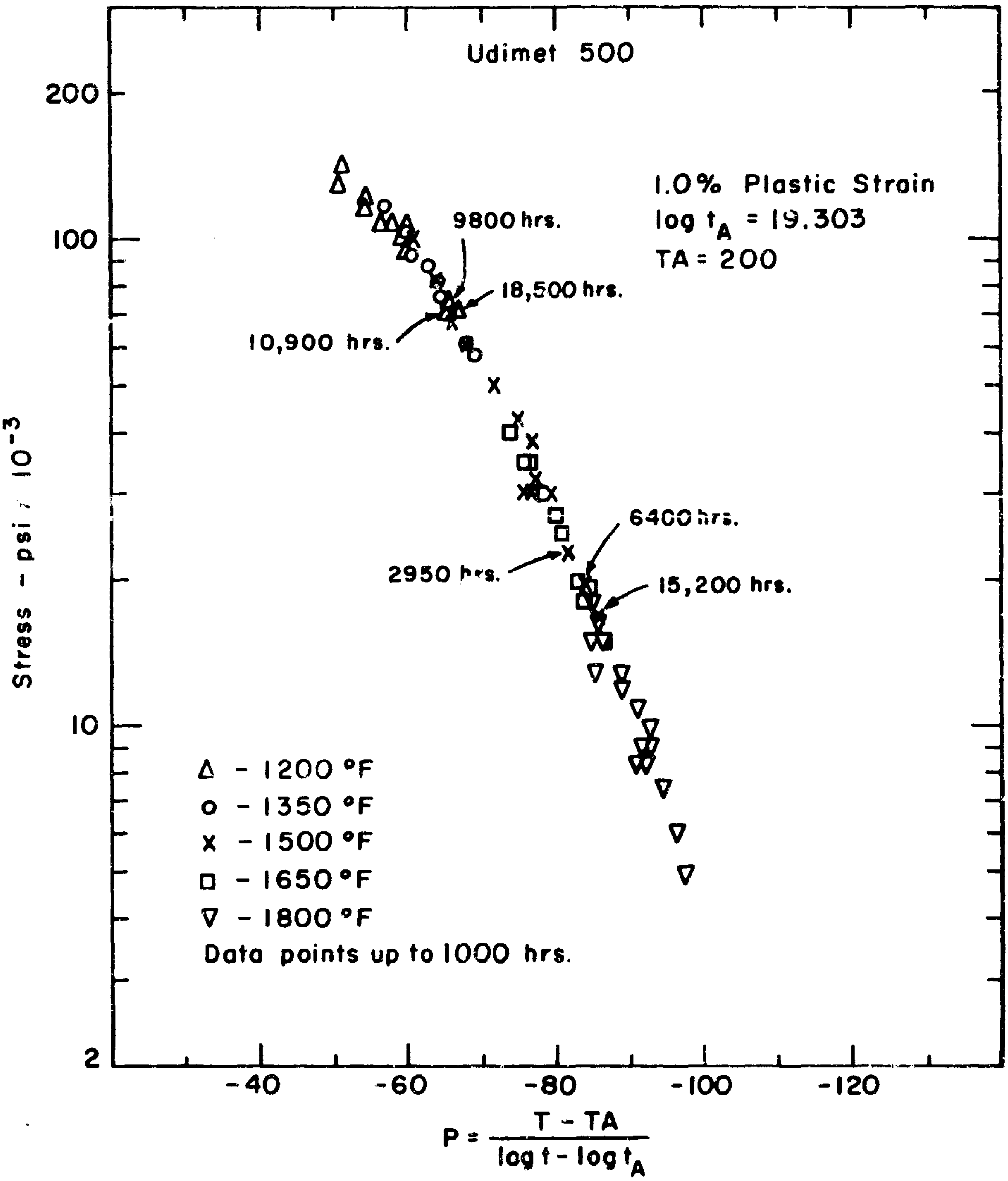


Figure 76: Manson—Haford plot, Udimet 500, 1.0% plastic strain.

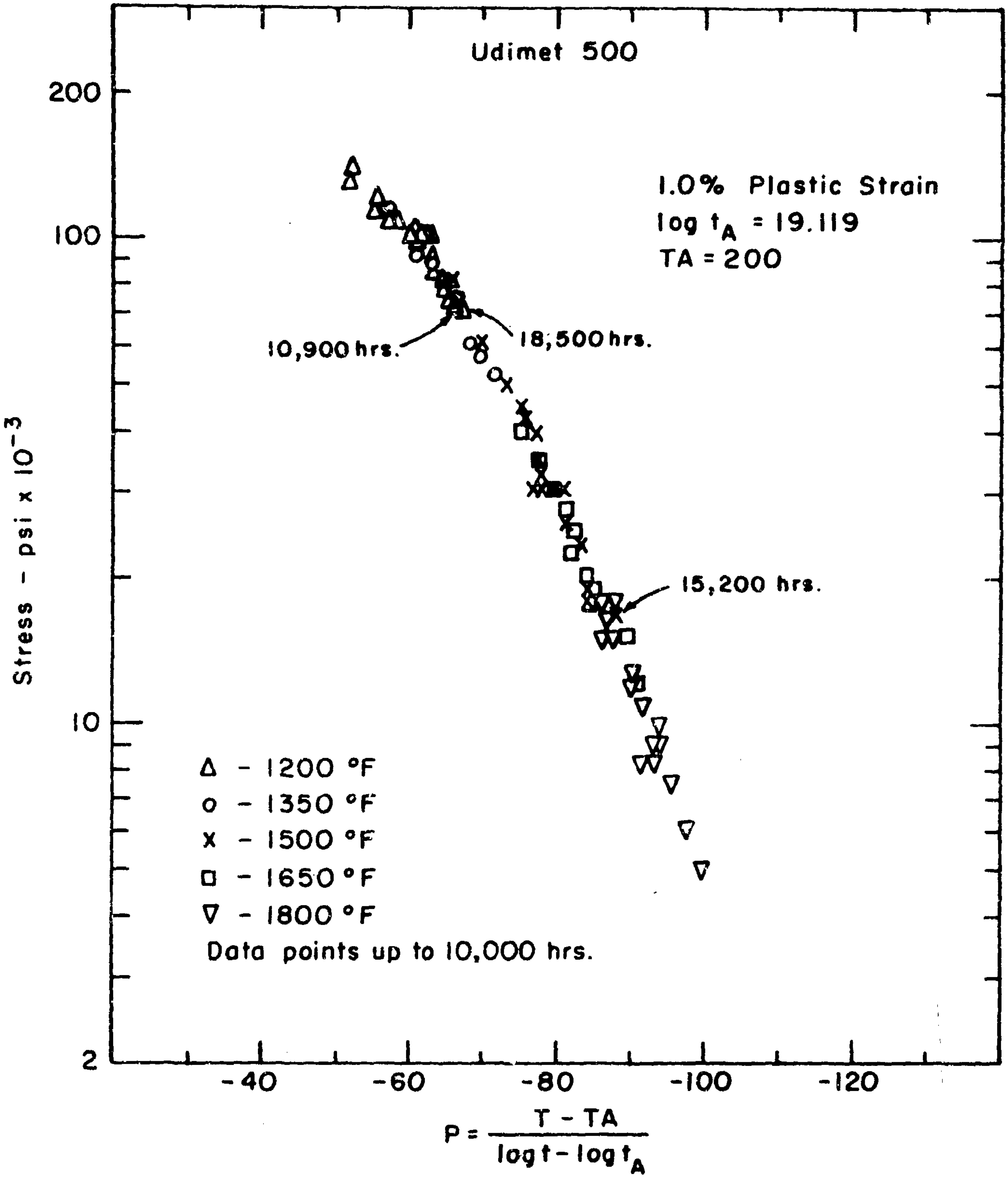


Figure 77: Manson—Haford plot, Udimet 500, 1.0% plastic strain.

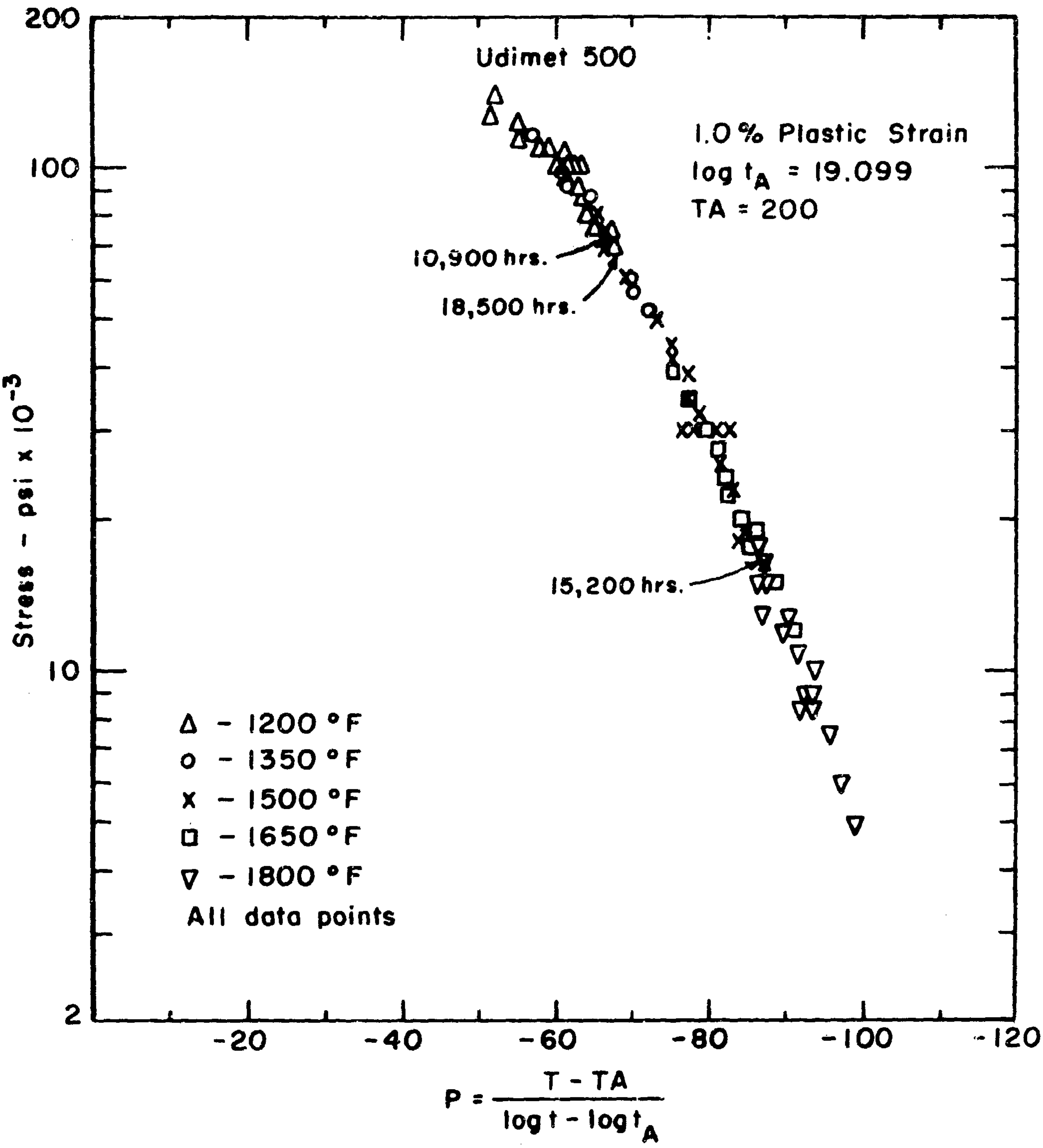


Figure 78: Manson—Haford plot, Udimet 500, 1.0% plastic strain.

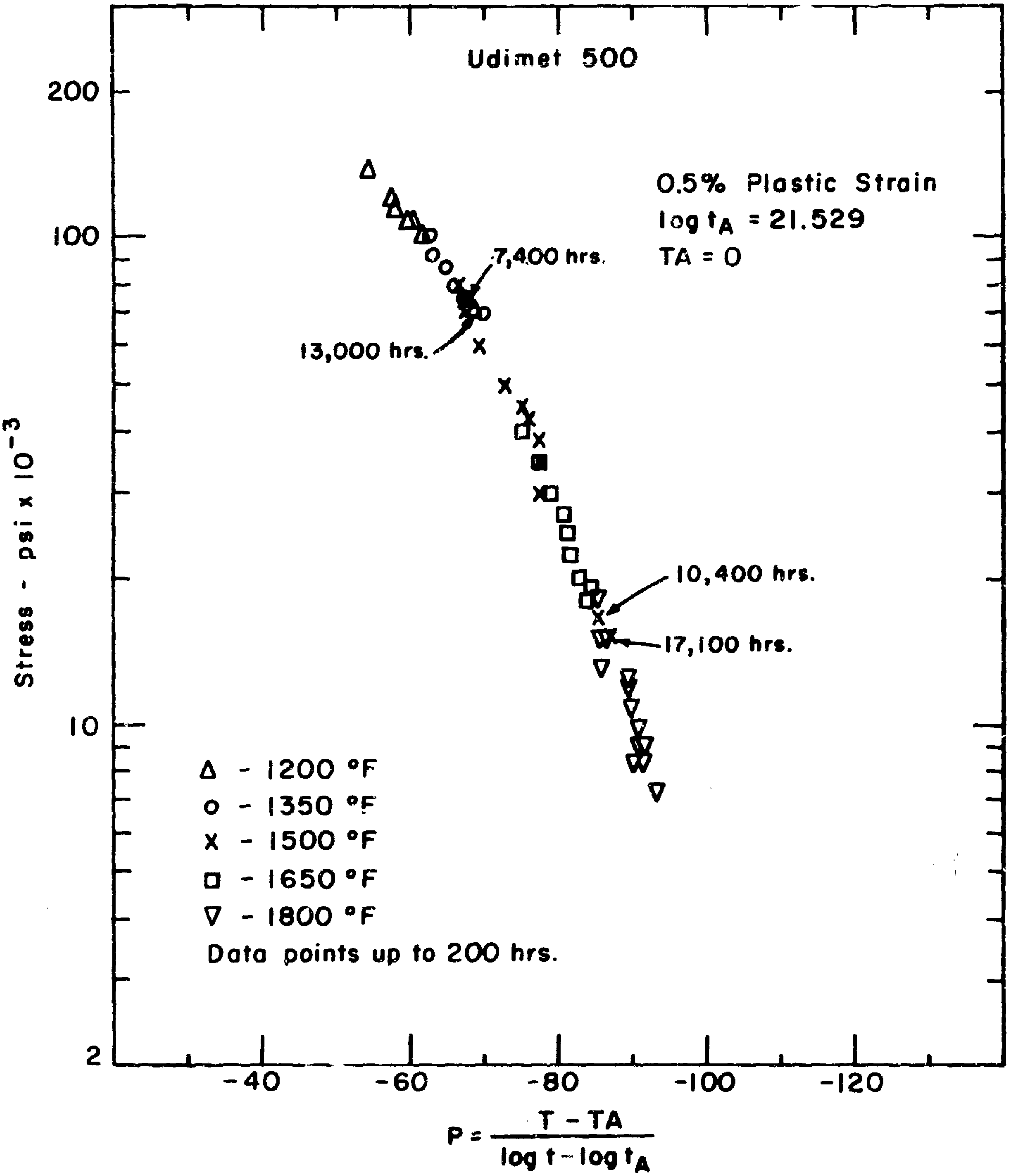


Figure 79: Manson—Haford plot, Udimet 500, 0.5% plastic strain.

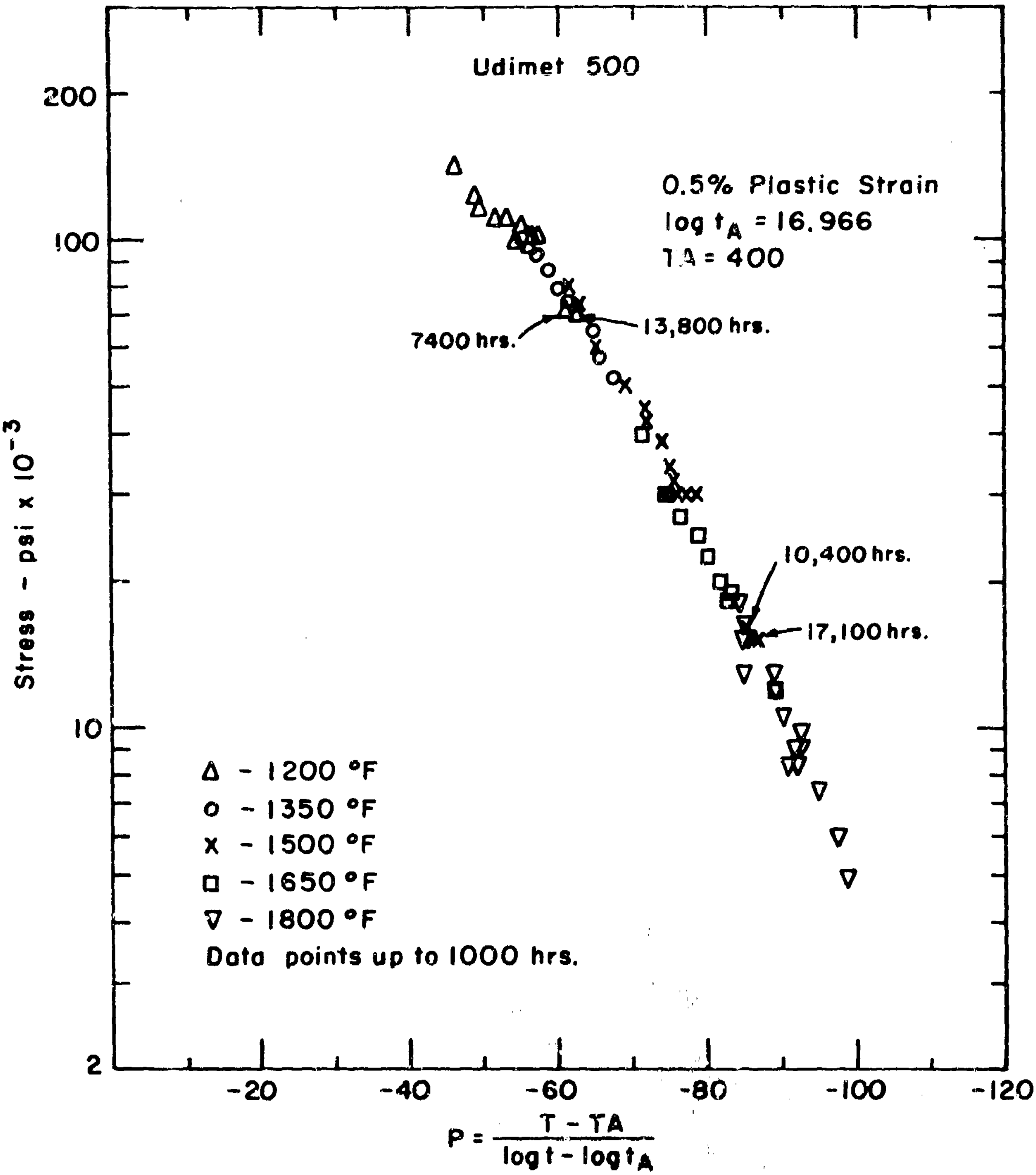


Figure 80: Manson—Haford plot, Udimet 500, 0.5% plastic strain.

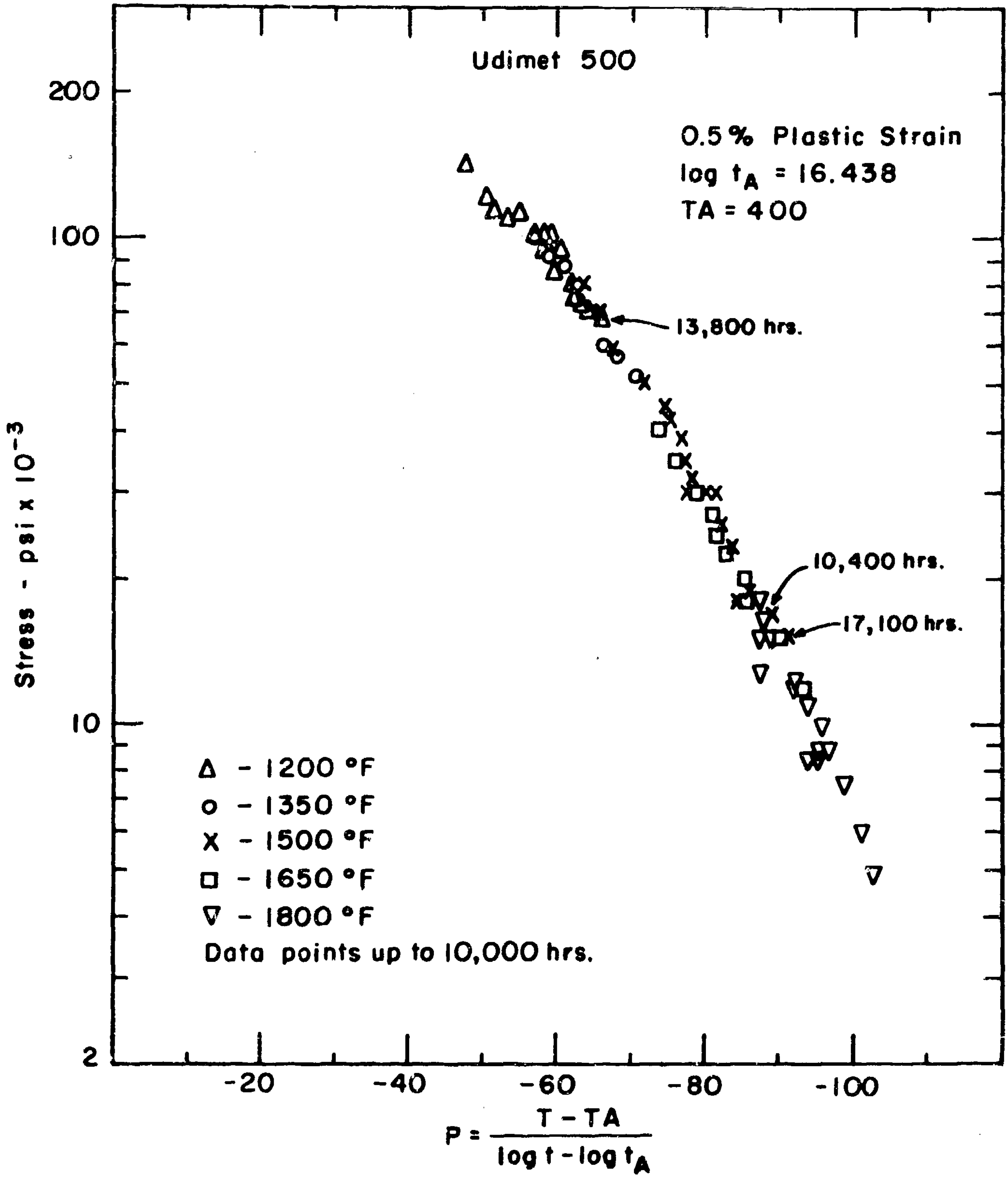


Figure 81: Manson—Haford plot, Udimet 500, 0.5% plastic strain.

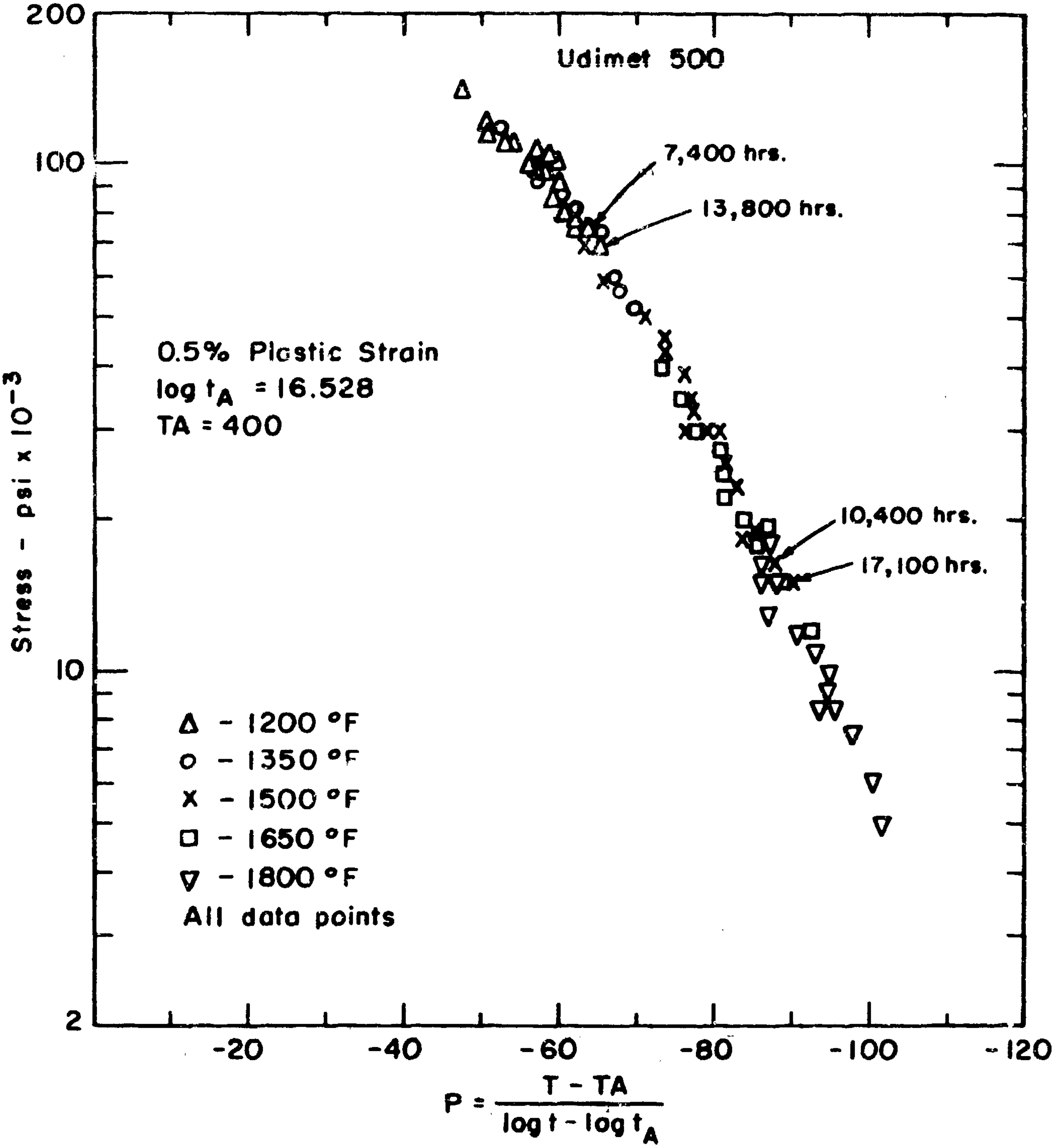


Figure 82: Manson—Haford plot, Udimet 500, 0.5% plastic strain.

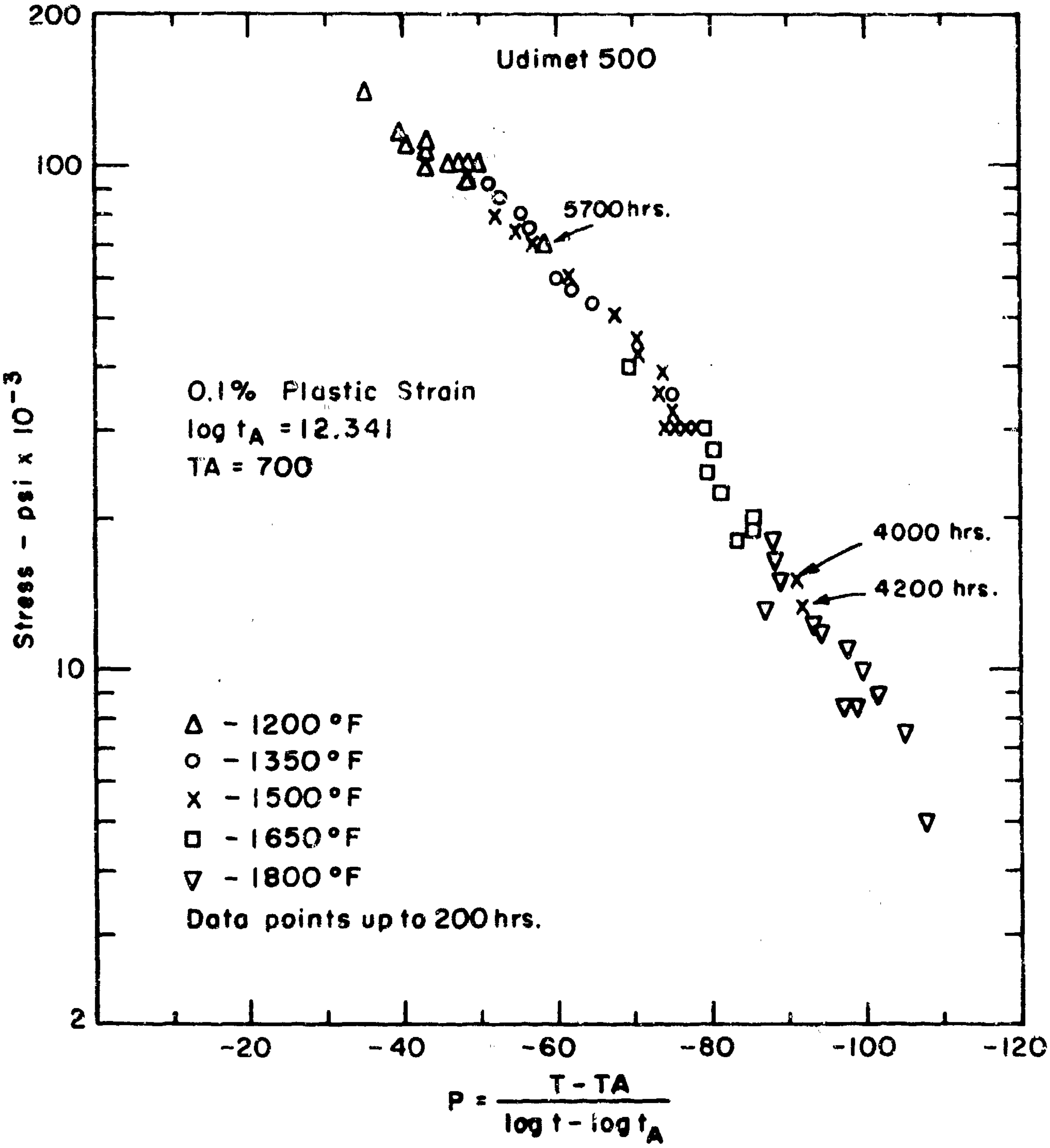


Figure 83: Manson–Haford plot, Udimet 500, 0.1% plastic strain.

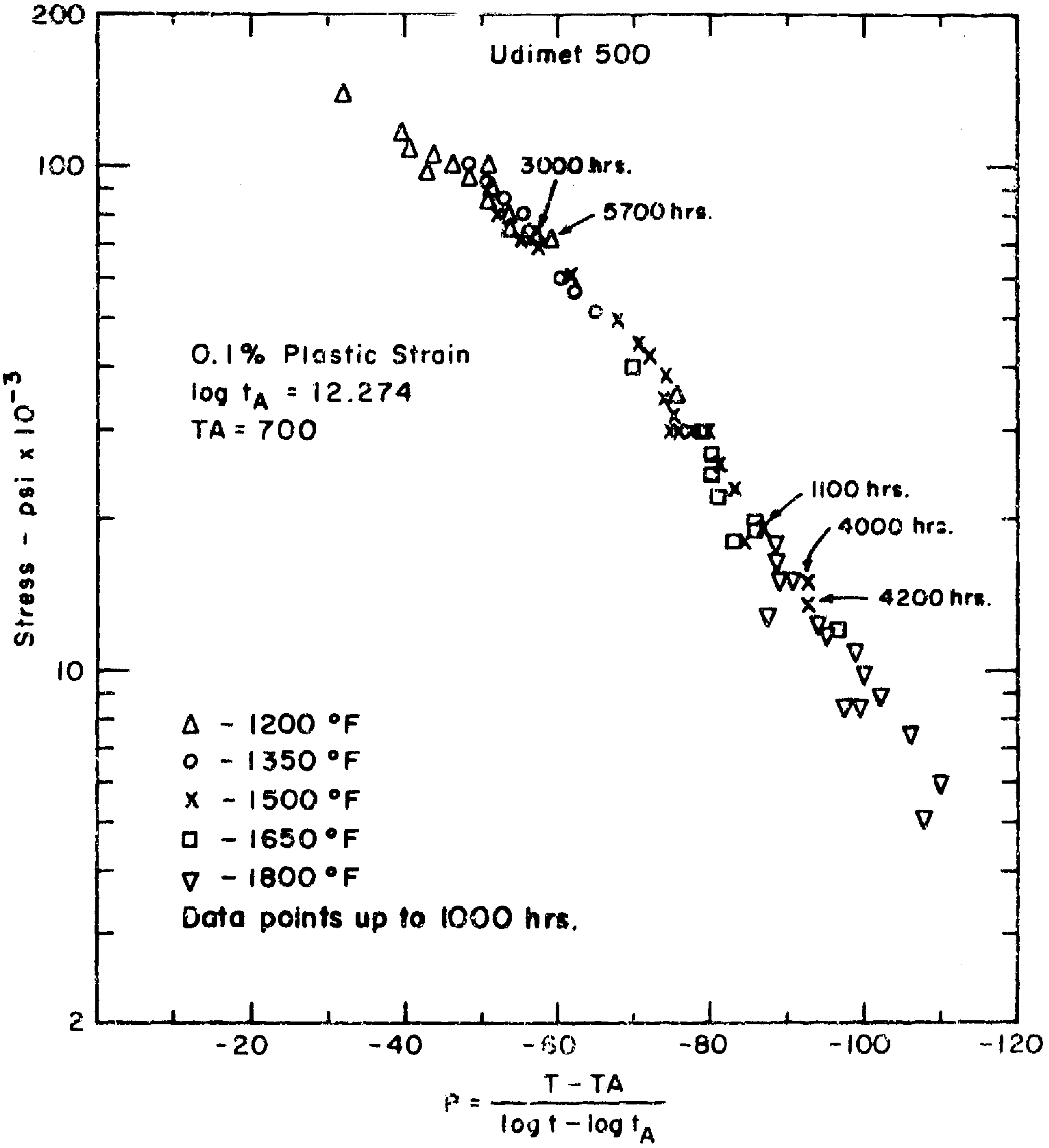


Figure 84: Manson—Haford plot, Udimet 500, 0.1% plastic strain.

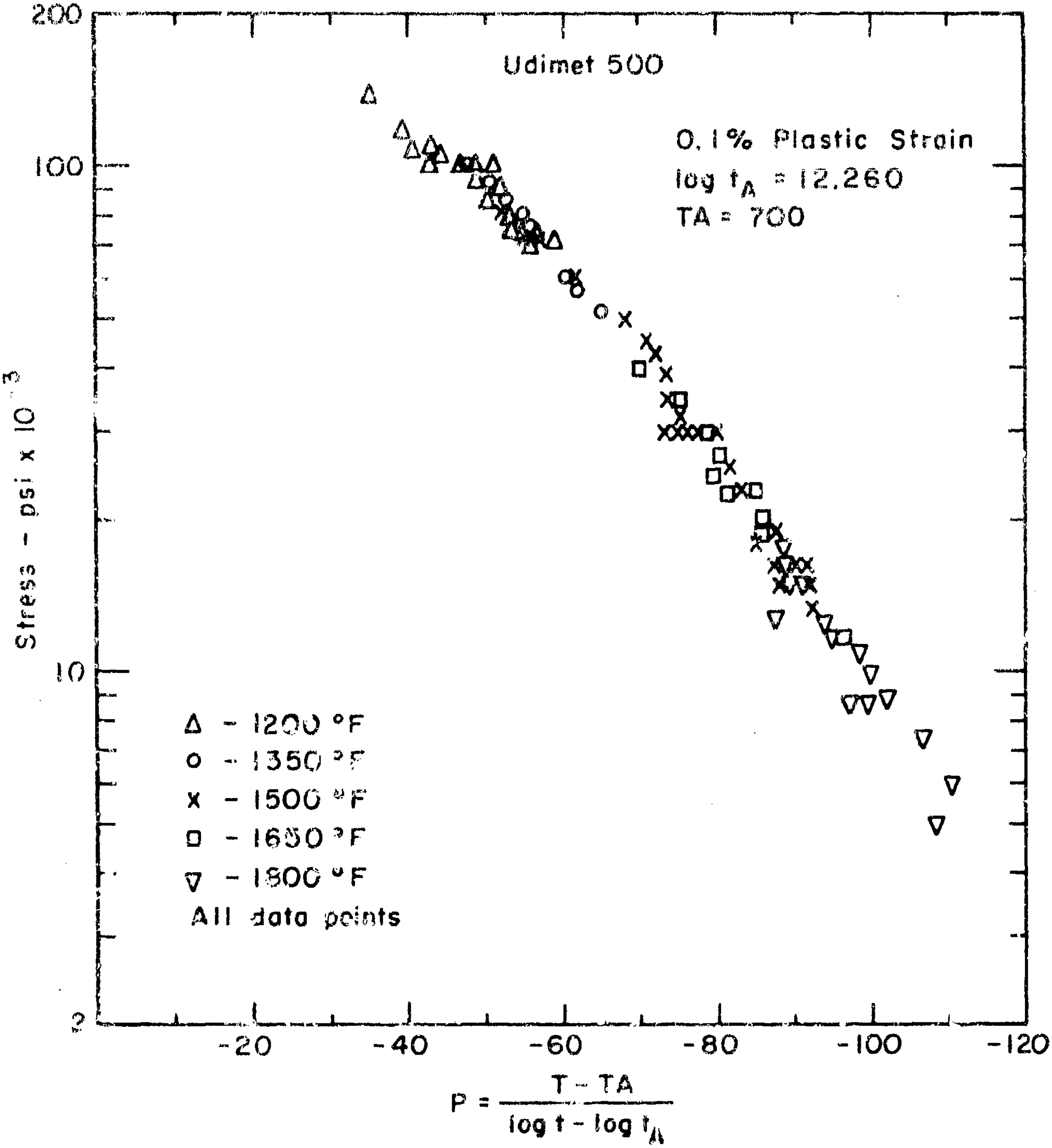


Figure 85: Manson-Haford plot, Udimet 500, 0.1% plastic strain.

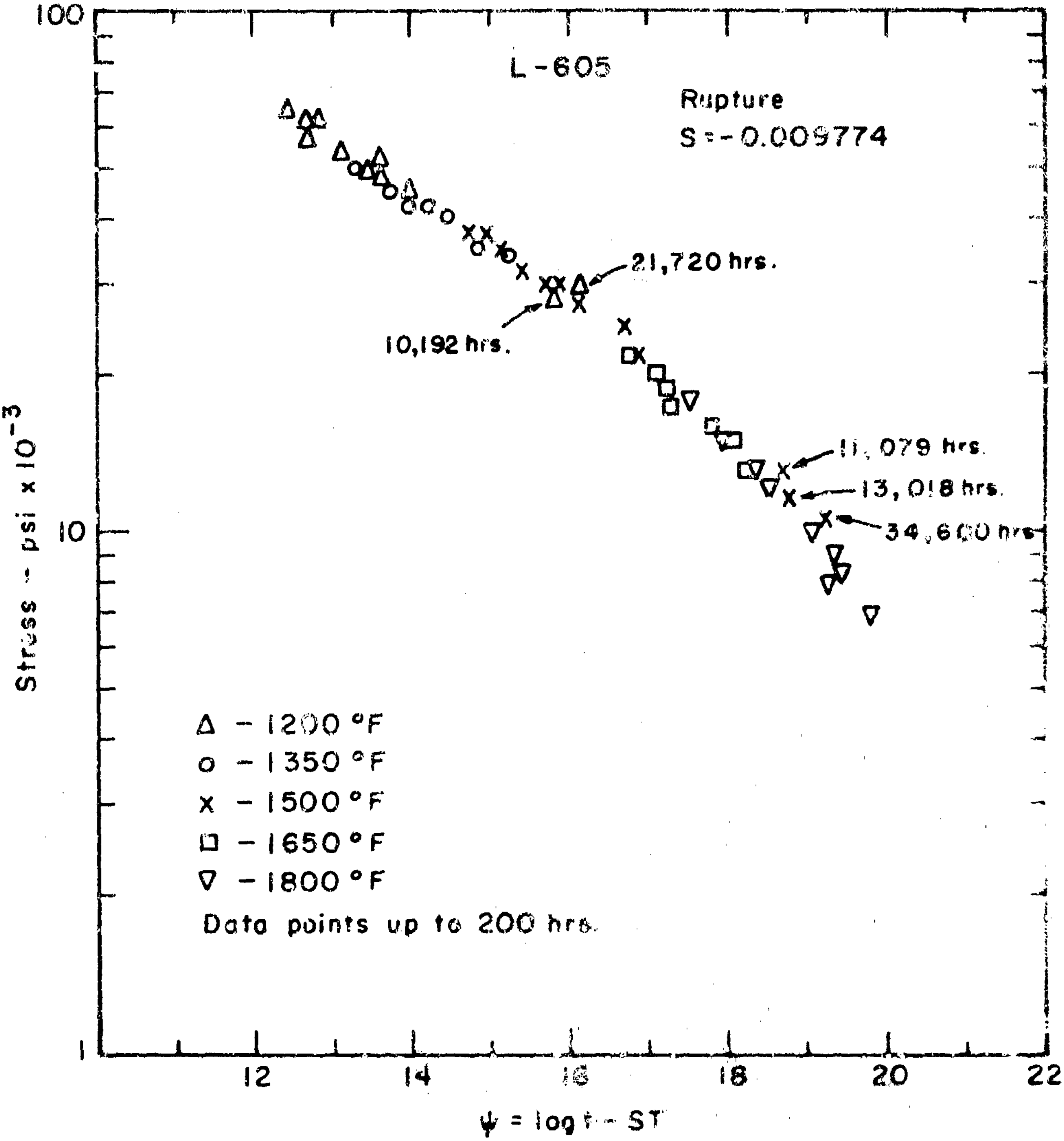


Figure 86: Manson-Haferd plot, L-605, rupture.

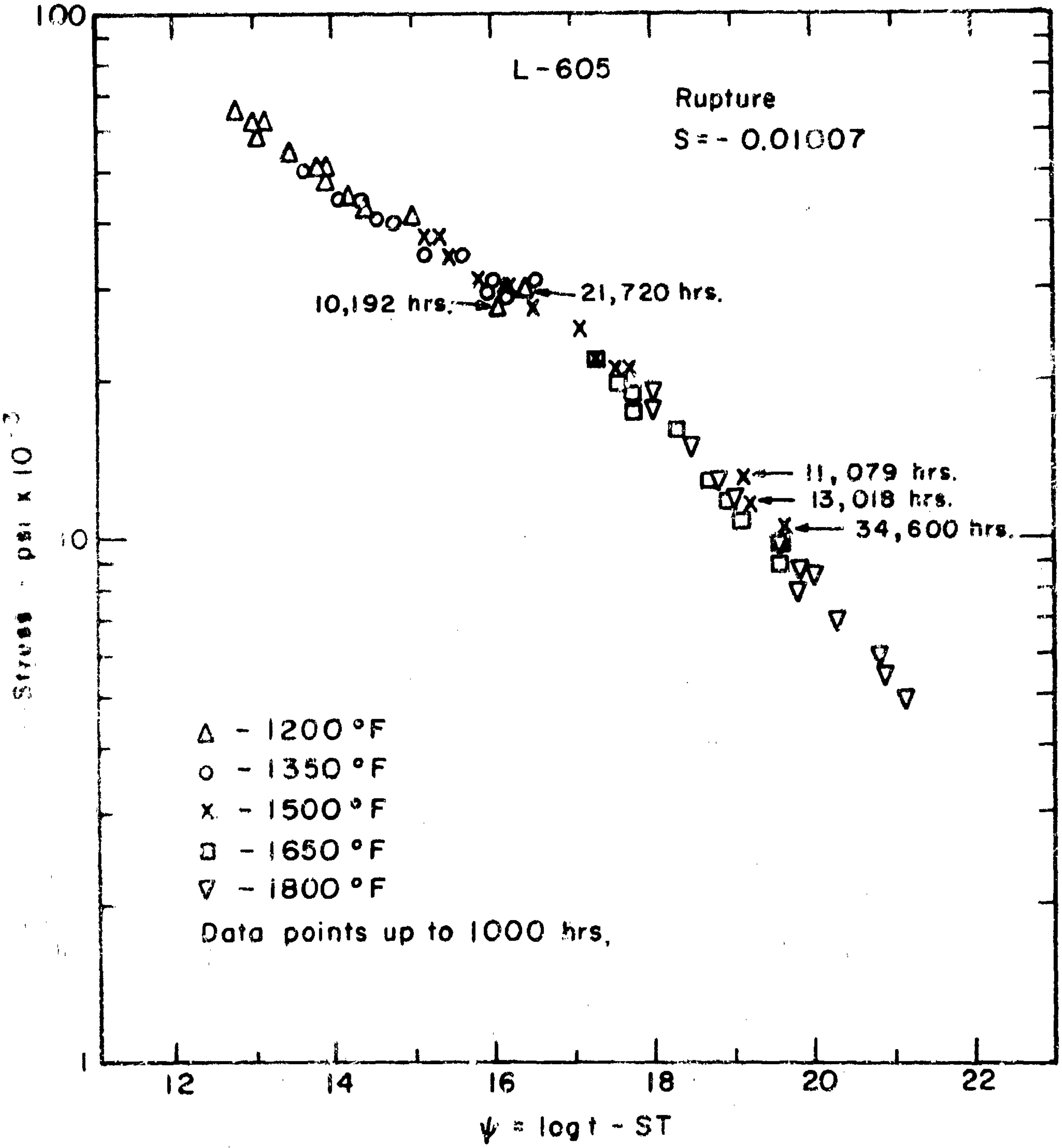


Figure 87: Manson-Haford plot, L-605, rupture.

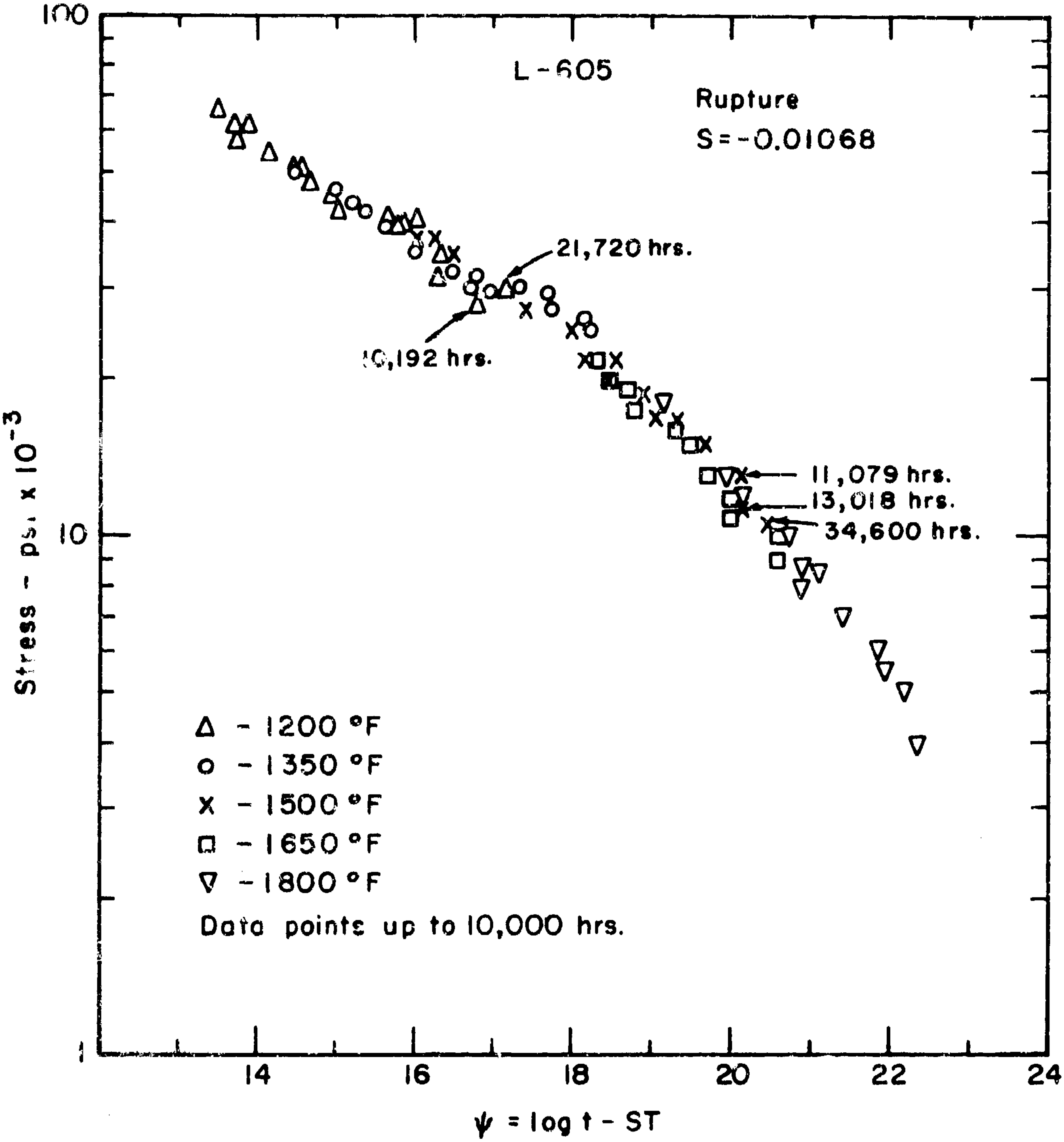


Figure 88: Manson—Haford plot, L-605, rupture.

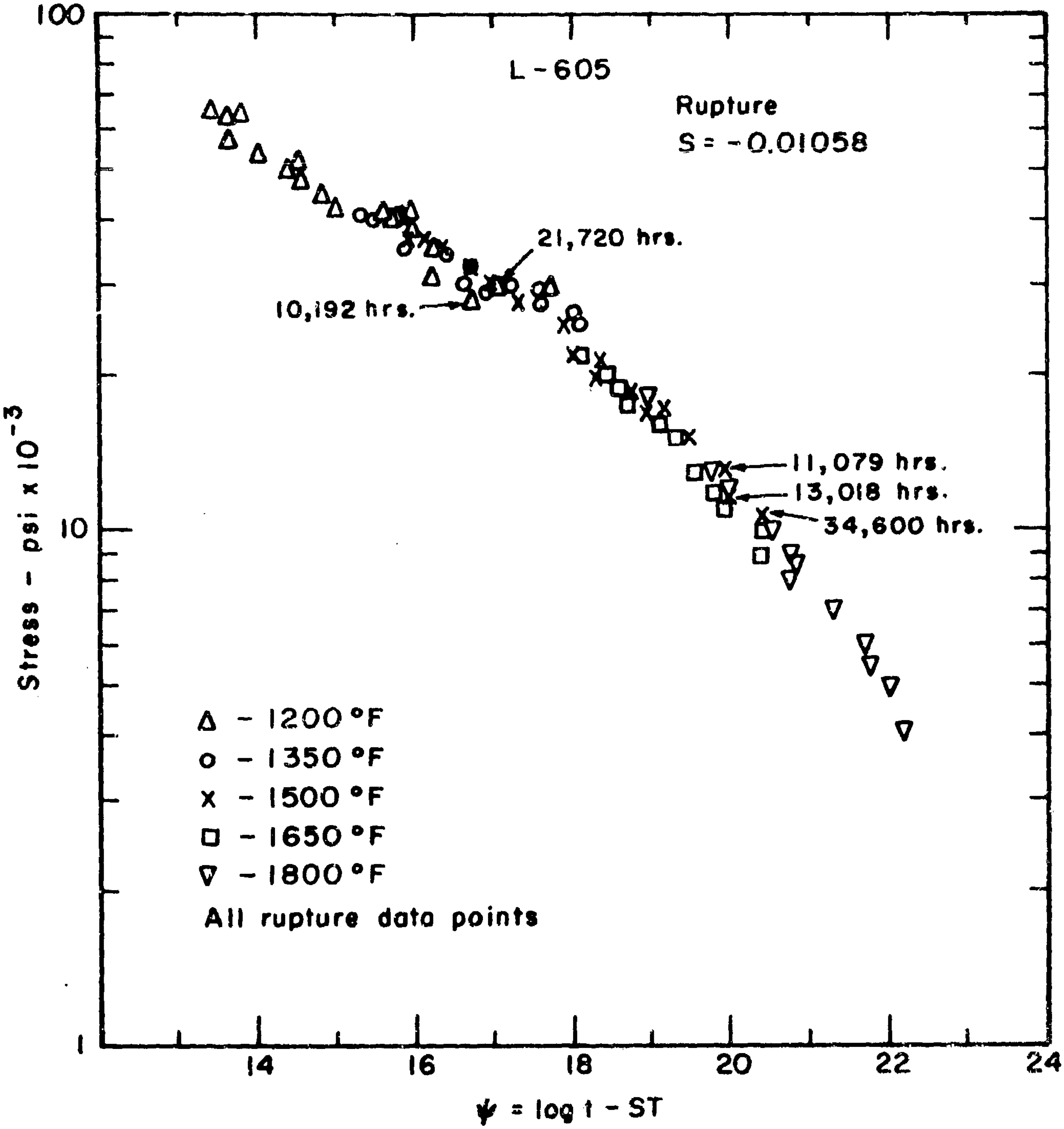


Figure 89: Manson-Haford plot, L-605, rupture.

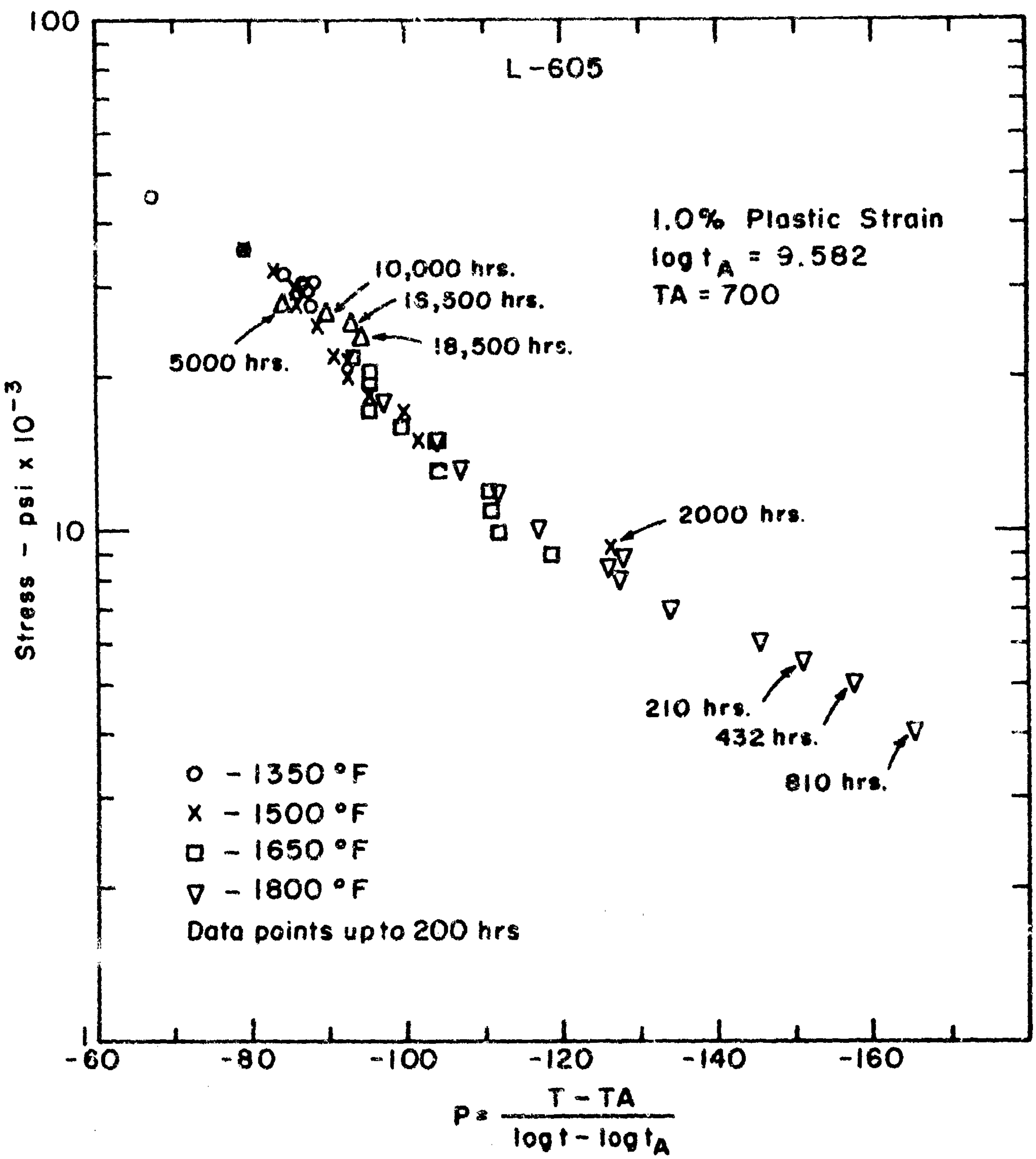


Figure 90: Manson-Haford plot, L-605, 1.0% plastic strain.

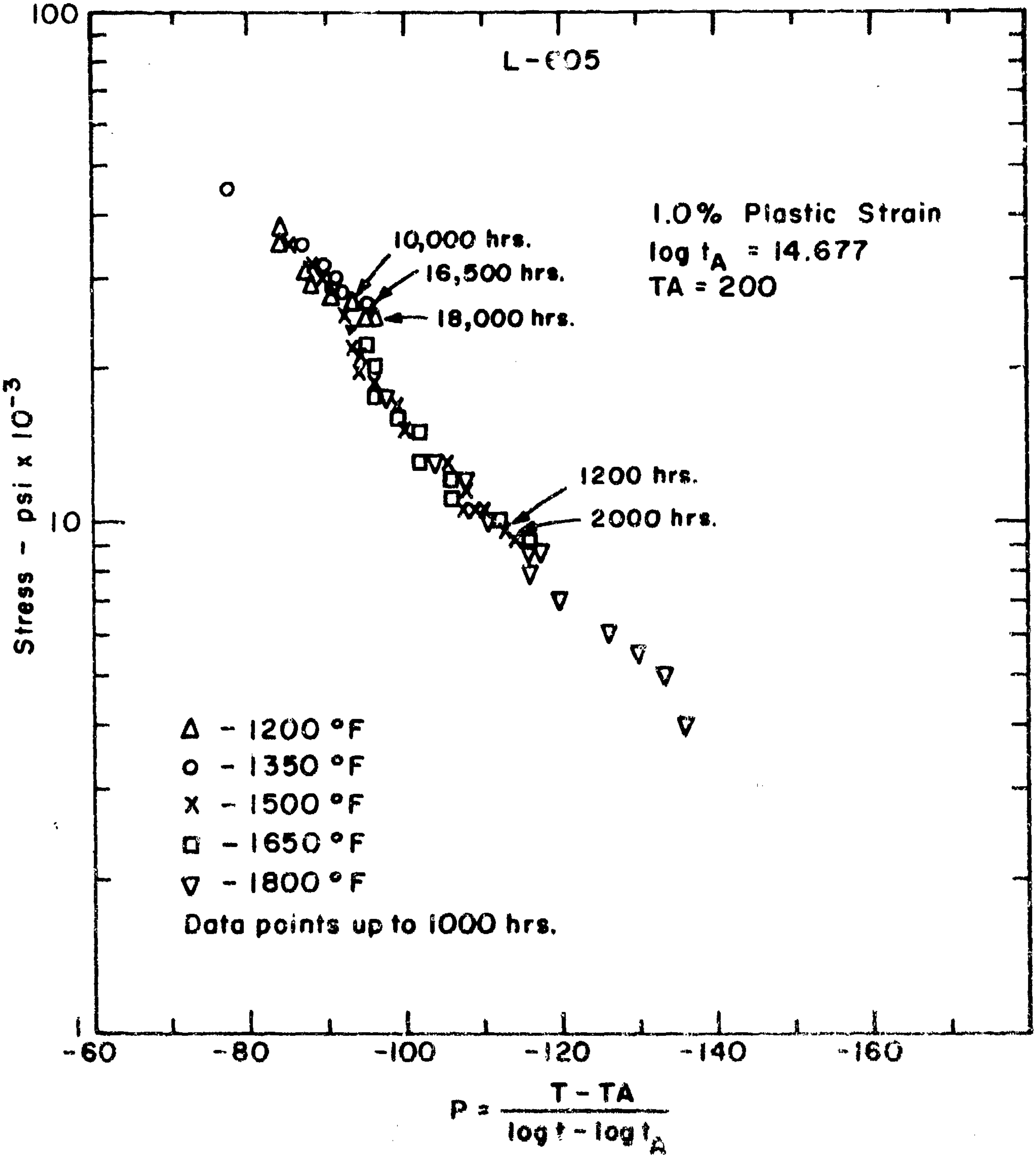


Figure 91: Manson-Haford plot, L-605, 1.0% plastic strain.

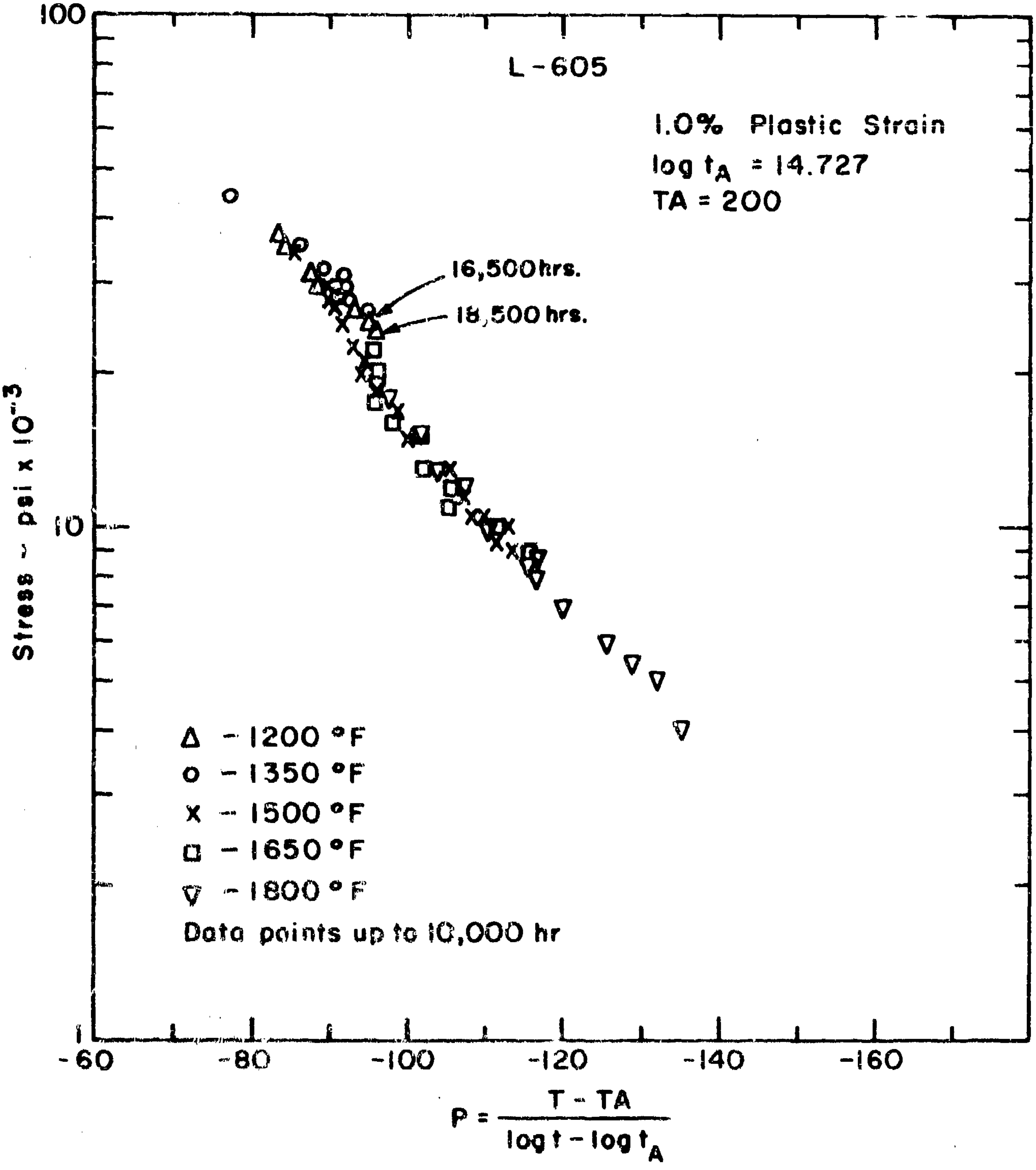


Figure 92: Manson-Haford plot, L-605, 1.0% plastic strain.

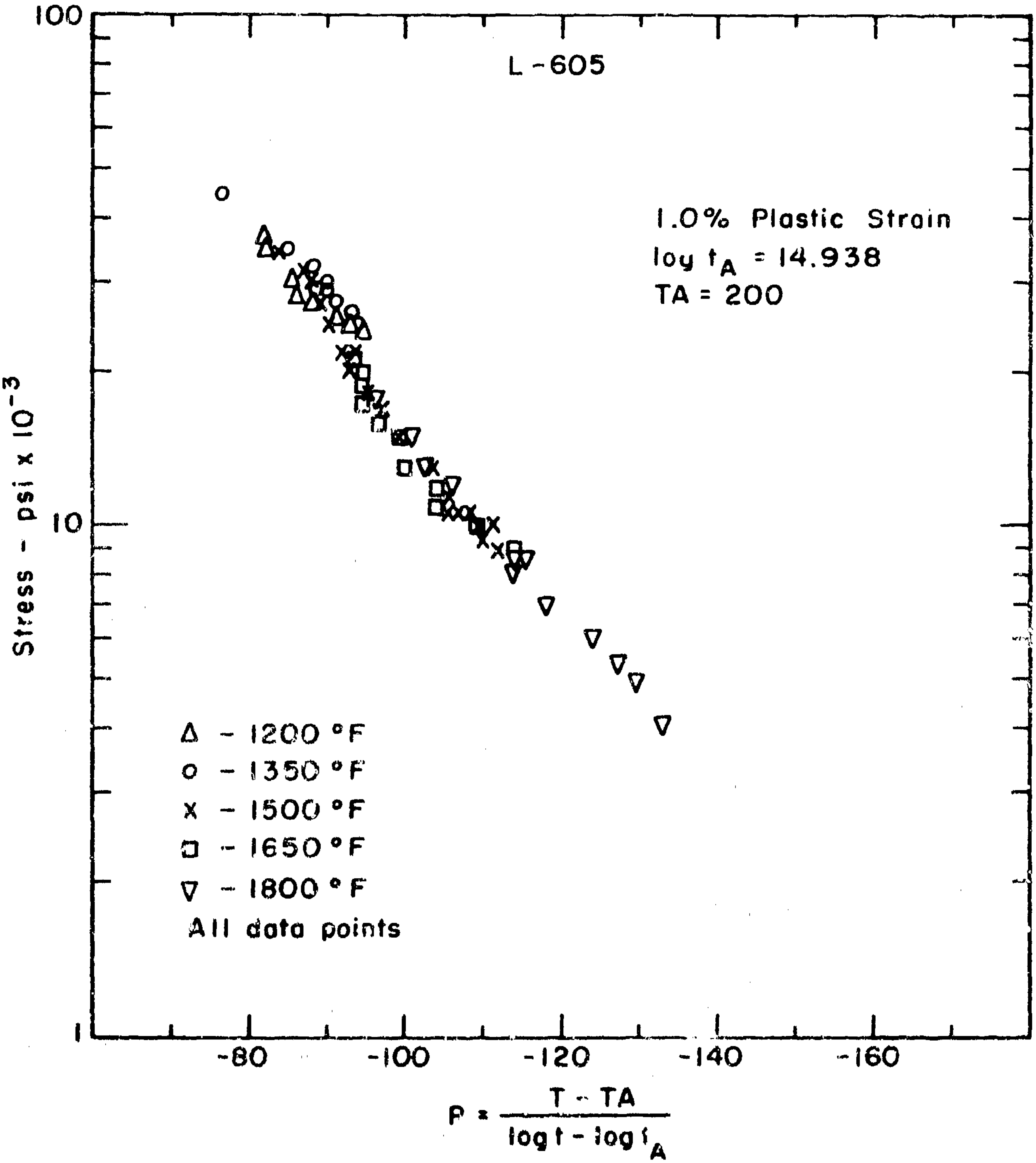


Figure 93: Manson-Haford plot, L-605, 1.0% plastic strain.

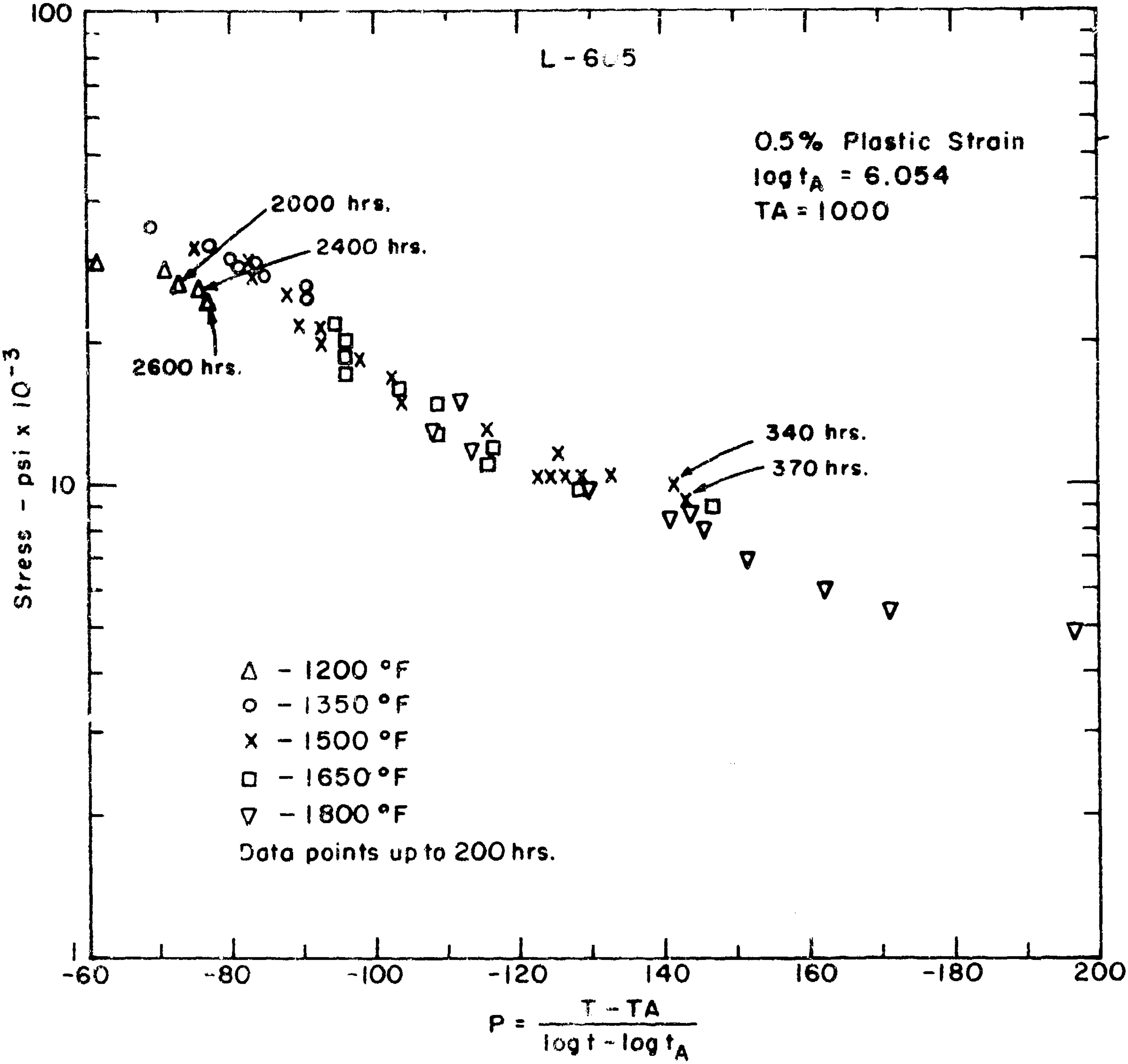


Figure 94: Hanson-Haford plot, L-605, 0.5% plastic strain.

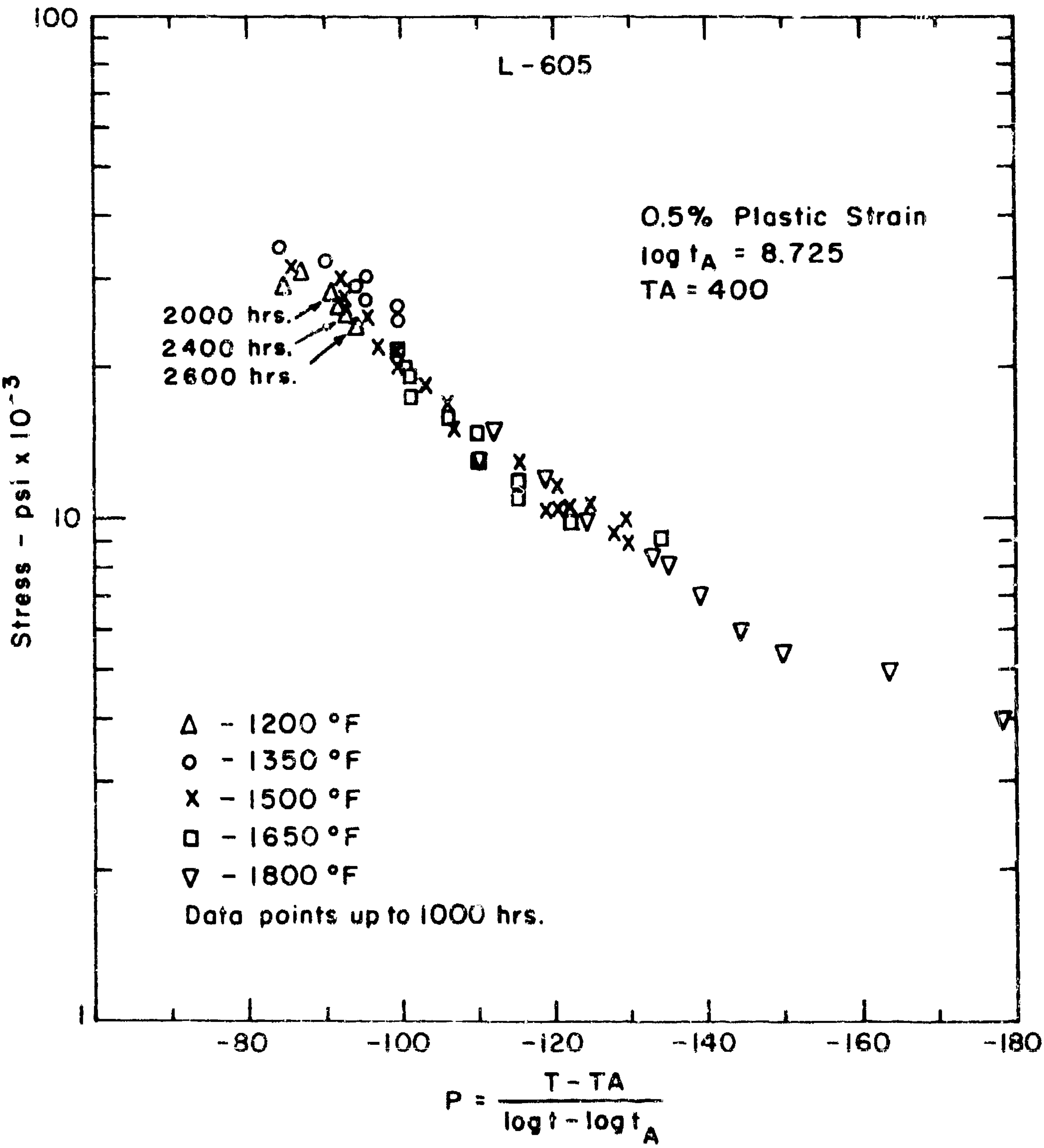
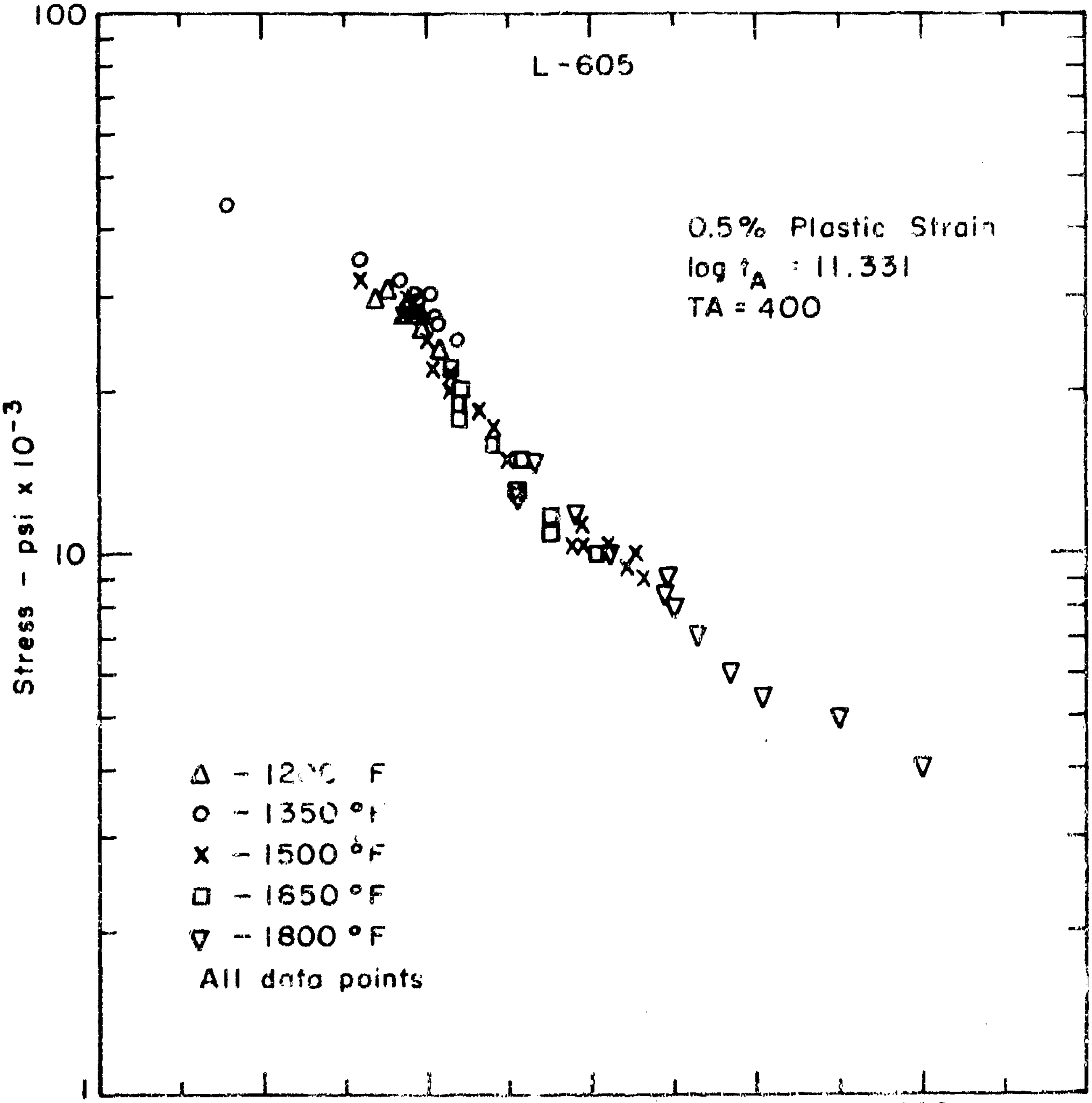


Figure 95: Hanson-Haford plot, L-605, 0.5% plastic strain.



$$P = \frac{T - TA}{\log t - \log t_A}$$

Figure 96: Hanson-Haford plot, L-605, 0.5% plastic strain.

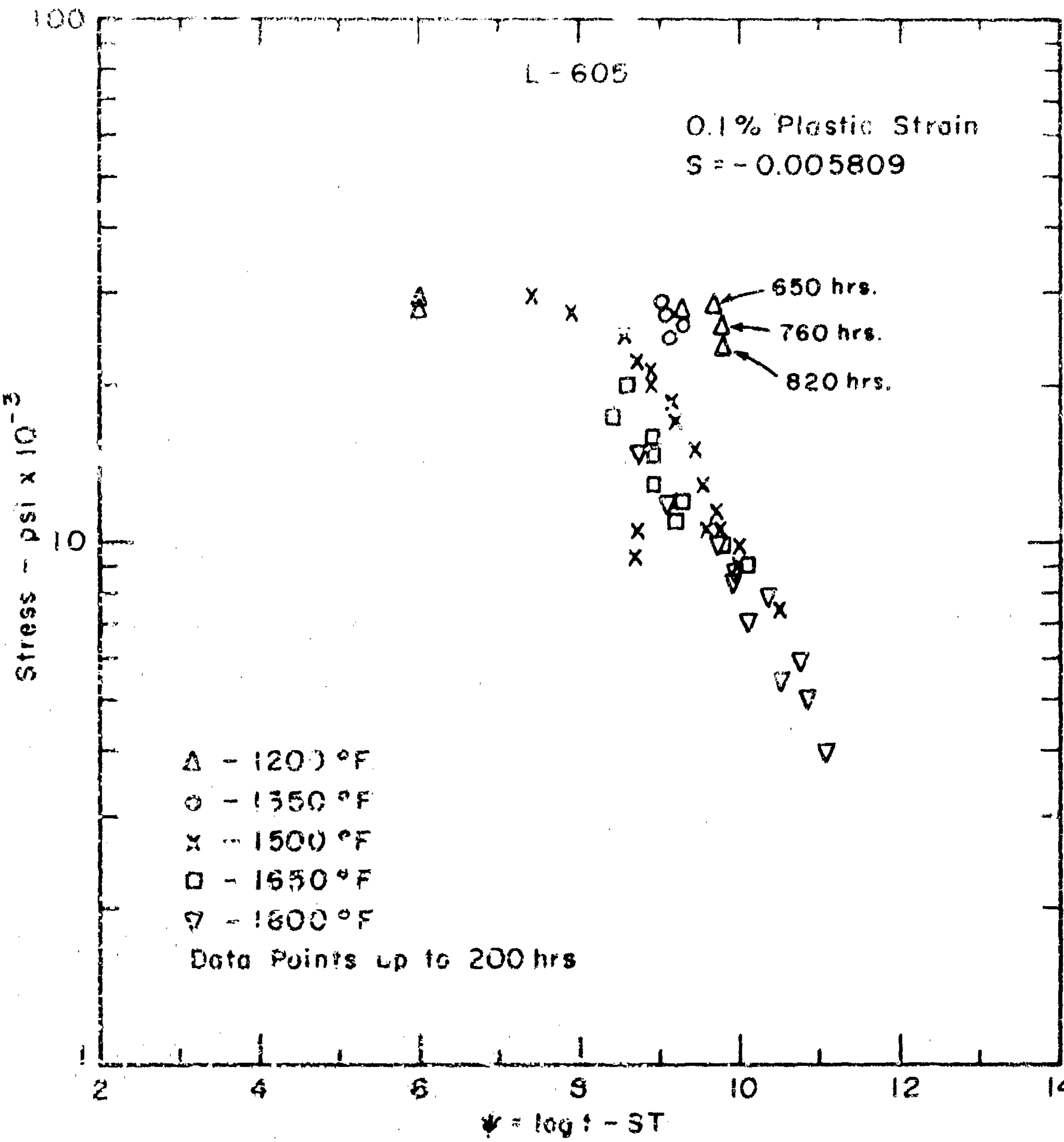


Figure 97: Hanson-Haford plot, L-605, 0.1% plastic strain.

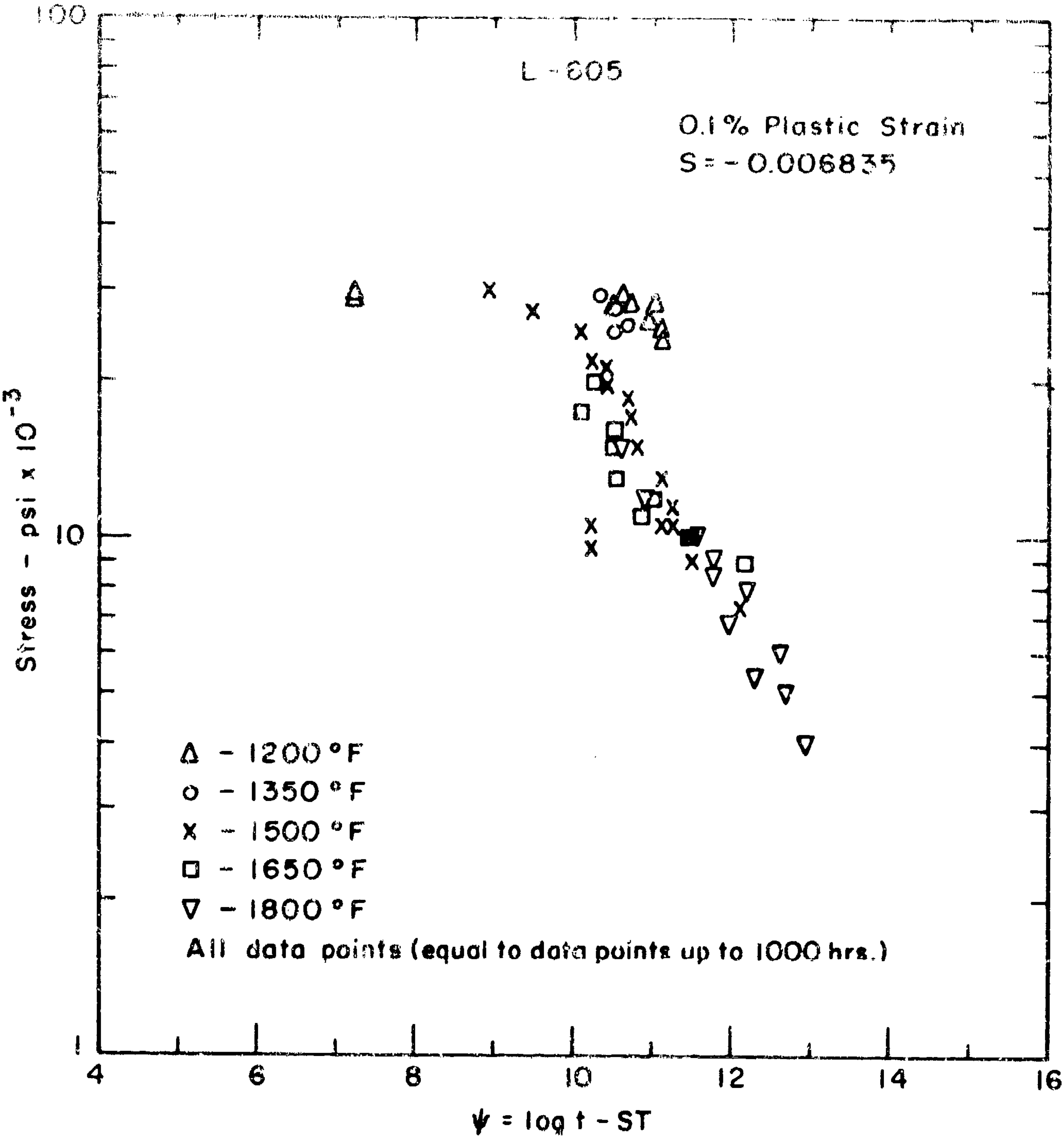


Figure 98: Hanson-Haford plot, L-605, 0.1% plastic strain.

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1. ORIGINATING ACTIVITY (Corporate author) New England Materials Laboratory 35 Commercial Street Medford, Massachusetts 02155	2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED 2b. GROUP

3. REPORT TITLE

MECHANISMS ASSOCIATED WITH LONG TIME CREEP PHENOMENA
PART II: EVALUATION OF LONG TIME CREEP RESULTS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Annual Summary Report - July 1964 to July 1966

5. AUTHOR(S) (Last name, first name, initial)

Widmer, R., Dhosi, J. M., and Grant, N. J.

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
March 1967	117	4

8a. CONTRACT OR GRANT NO. AF 33(615)-2452	9a. ORIGINATOR'S REPORT NUMBER(S) AFML-TR-65-181, Part II
b. PROJECT NO. 7351	
c. TASK NO. 735106	9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)
d.	

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Research and Technology Division Air Force Materials Laboratory (MAMD) Wright-Patterson AFB, Ohio 45433

13. ABSTRACT

A creep-rupture investigation was conducted on two (2) high temperature alloys: a nickel-base age hardened alloy, Udimet 500, and a cobalt-base alloy, L-605. Creep-rupture tests were conducted over a range of rupture lives from 1 -35,000 hours at 1200, 1350, 1500, 1650 and 1800°F. Some long time tests are in progress and lives of approximately 50,000 hours are expected.

The microstructure of all broken specimens was examined with various techniques and an attempt was made to correlate specific structural changes with the mechanical properties.

Several different parameter techniques were examined to determine their utility in correlating and extrapolating creep and rupture data.

The strength and the limitations of parametric extrapolation was extensively discussed with the example of the Manson-Haford parameter for which a computer program was available.

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